UNIVERSITY OF ALBERTA

THE DUNVEGAN SANDSTONE OF THE TYPE AREA

A THESIS

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OF MASTER OF SCIENCE

DEPARTMENT OF GEOLOGY

by

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The undersigned certify that they have read, and recommend to the Faculty of Graduate Studies for acceptance, a thesis entitled "The Dunvegan Sandstone of the Type Area", submitted by Jhumar Mal Tater, B.Sc.(Hons.), M.Sc.(Bihar), A.I.S.M., in partial fulfilment of the requirements for the degree of Master of Science.

ABSTRACT

Sandstones of the Dunvegan Formation from the type area are described with respect to texture, composition, and K-Ar dates from K-feldspars.

Investigations on grain size distribution indicate that the sandstones are submature and medium-grained. On the basis of size parameters it is inferred that the provenance was not restricted to one type of rock and that the sorting effect of the environment was poor.

The composition of the sandstones suggest that sedimentary rocks were probably major contributors to the sediment, and igneous and metamorphic rocks supplied a lesser proportion of the detritus.

K-Ar dates from the K-feldspars of two samples agree with the Late Jurassic age assigned to early orogenies in the Cordillera to the west. Differences in the two dates support the hypothesis that the Dunvegan sediments were derived by unroofing of rising Cordilleran batholiths to the west.

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INTRODUCTION

General Statement

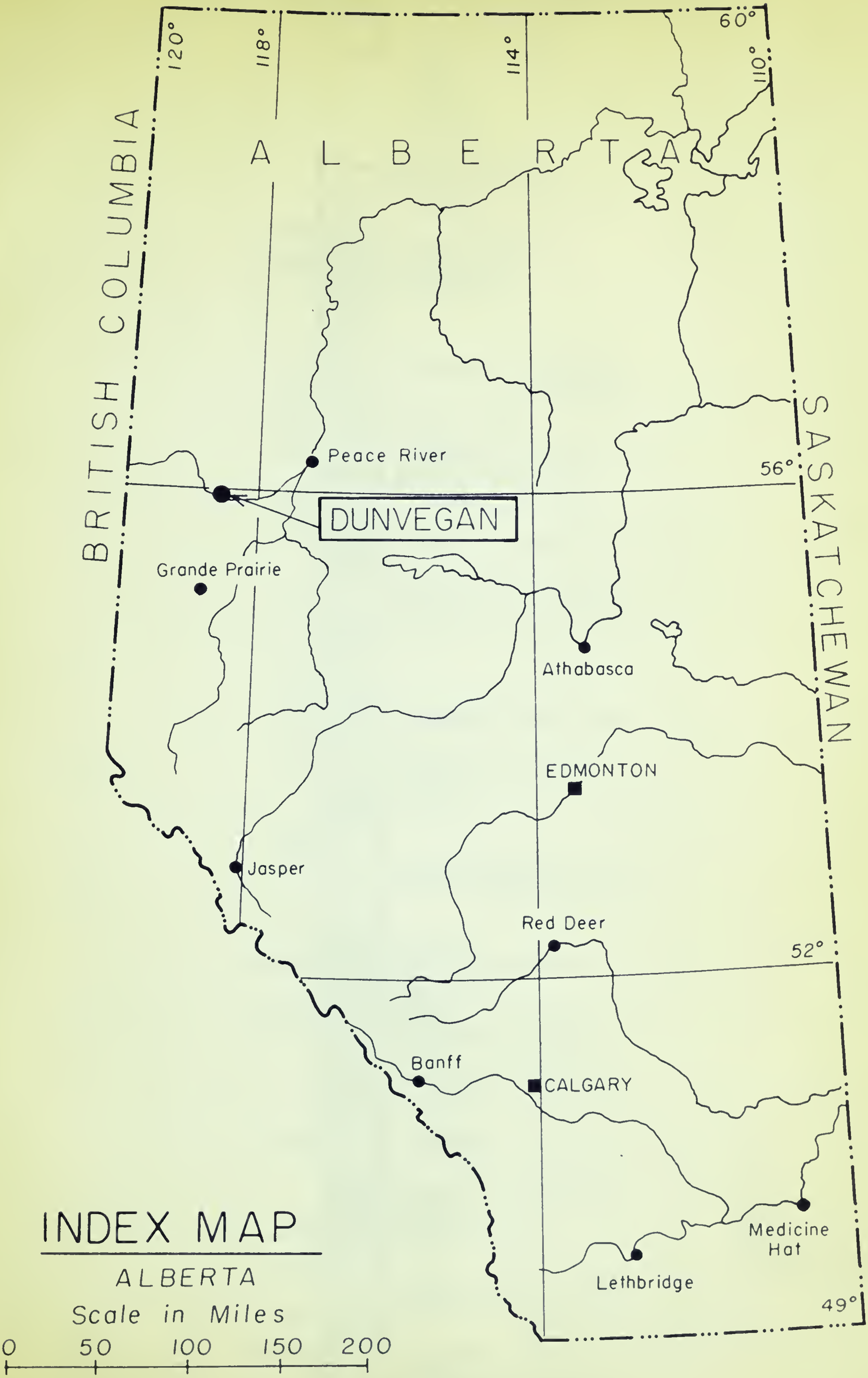
This thesis presents a study of texture and composition of Dunvegan sandstones from the type section of the Dunvegan Formation. Although two type sections of the Dunvegan Formation were designated by Dawson in 1881: one on the Peace River at Dunvegan, Alberta, and another on the Pine River at East Pine, British Columbia; the former is now usually considered the type area of the formation (Stelck, 1962; p. 13), and was the one examined in the present study (Figure 1).

A little over 400 ft. of the formation is exposed at Dunvegan crossing close to the bridge (Lat. 55°56'N, Long. 118°36'; Twp. 80, Rge. 4, W6 Meridian). Some part (less than 10 feet) of the formation is apparently below the water level of the Peace River. The 24 samples studied in this work were collected from the outcrop and represent all the sandstone phases of the formation in this section. The position of the samples in the vertical section of the formation is shown in figure 2.

Previous Work

In 1881, G.M. Dawson introduced the name "Dunvegan Formation" for what he called the "Lower sandstone and shales of the lowest forks of Pine River and parts of Peace River valley". Dawson's work was of an exploratory nature and covered the area between Port Simpson (on the Pacific Coast) and Edmonton. A portion of the northern part of British Columbia and the Peace River country was also included in the study.

R.G. McConnell's (1892) work was also of a reconnaissance nature. He notes that the Dunvegan Sandstone of the Peace River section is not represented at the Athabasca River section.



ALBERTA
BRITISH COLUMBIA
SASKATCHEWAN
120°
118°
114°
110°
60°
56°
52°
49°
Peace River
DUNVEGAN
Grande Prairie
Athabasca
EDMONTON
Jasper
Red Deer
Banff
CALGARY
Medicine Hat
Lethbridge
INDEX MAP
ALBERTA
Scale in Miles
0 50 100 150 200

Figure 1

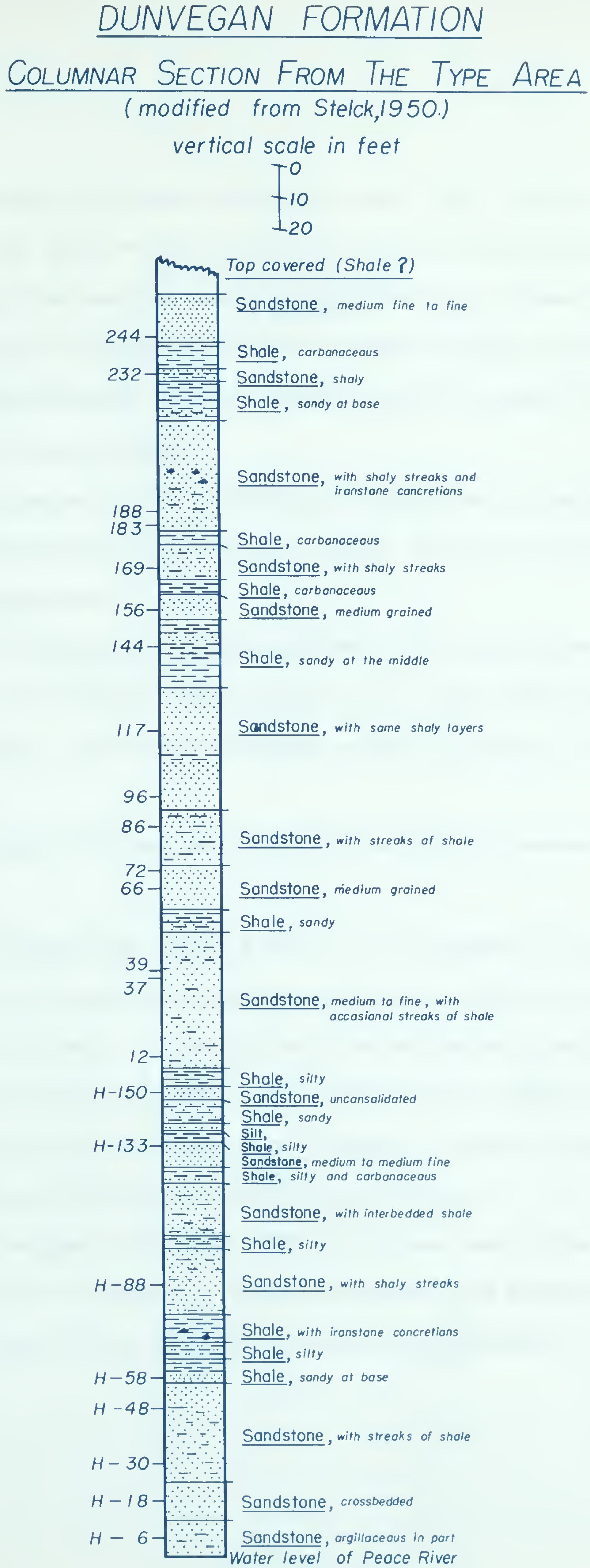


Figure 2.

Position of Samples in Vertical Section

Studies by McLearn (1919, 1935, 1943, 1945), McLearn and Henderson (1944), Warren (1930, 1933), Warren and Stelck (1940) have contributed much towards the knowledge of the formation, especially its palaeontology. Warren and Stelck (ibid) placed the Pouce Coupe Sandstone and Doe Creek Sandstone as sandstone members of the Dunvegan Formation, but these members have been retained in the Kaskapau by the Geological Survey of Canada.

Wickenden and Shaw (1943) report the presence of cross-bedding in the sandstones of the formation in the Pine River Valley. They have also recorded the presence of some conglomerate.

In the study of the geology adjacent to the Alaska Highway between Fort St. John and Fort Nelson, British Columbia, C.O. Hage (1944) reports that on the Alaska Highway, the Dunvegan Formation consists of sandstone, shale and some conglomerate.

Kindle (1944) mapped the Nelson Formation and compared it with the Dunvegan Formation.

Williams (1944) mapped a formation of conglomerate and sandstone on Table, Steamboat, and Teepee Mountains and considered it to be of the same age as the Dunvegan of the south, and identical with the Fort Nelson Formation.

Contributions by Stelck (1950), Stelck and Wall (1955) and Stelck *et al.* (1958) have been mostly palaeontological studies (including micropalaeontology) and add to our present knowledge of the Dunvegan sediments.

Beveridge and Folinsbee (1956) studied some heavy mineral assemblages of the formation in an attempt to correlate the Mesozoic and Cenozoic sedimentary rocks of Alberta basin with the batholithic intrusives of the Cordillera.

CHAPTER TWO

STRATIGRAPHY

The Dunvegan Formation

G.M. Dawson (1881) used the name Dunvegan Formation for a group of fresh water sandstones and shales occurring at Dunvegan, an old trading centre on the Peace River in Alberta. From more recent accounts, the formation also includes some brackish to marine phases.

The formation consists of light grey, massive, crossbedded sandstones, thick dark grey shales, flat ironstone concretions, thin-bedded sandstone and shale, and rare calcareous layers. Thin coal seams have also been reported to occur in the formation but these are rare.

According to Gleddie (1954; p. 494), the lithologic units themselves are lenticular and, although the coarse sandstone phases are in many places replaced in part by lenses of siltstone and shale, the zones have more or less lateral continuity because new lenses of similar sandstone normally reappear within them.

The idea that the formation is of deltaic nature is well established in the minds of students of geology in western Canada. The present study does not do away with this assumption, rather, based on textural implications, it is suggested that conditions close to that of a beach environment probably prevailed in certain sandstone phases of the type section.

Extent and Size of the Formation

The Dunvegan Formation has a wide distribution in parts of northeastern British Columbia and northwestern Alberta. It outcrops along the valley of Peace River from Cache Creek to near the mouth of the Smoky, and probably underlies the

Table 1.

Series	Stage	Upper Pine River (B. C.)	East Pine (B.C.)	Fort St. John (B.C.)	Pouce Coupe (Alberta)	Dunvegan (Alberta)	Lower Smoky River (Alberta)	Lower Athabasca River (Alberta)	Sikanni Chief River (B.C.)	Liard River (B.C.)
UPPER CRETACEOUS	Turonian	SMOKY GROUP: Sandstones of Tuskoola Mountain	KASKAPAU	KASKAPAU	KASKAPAU	KASKAPAU	KASKAPAU	LA BICHE	eroded	KOOTANEELEE
							2nd Specks			Missing
	Cenomanian	DUNVEGAN	DUNVEGAN	DUNVEGAN	DUNVEGAN	DUNVEGAN	DUNVEGAN		DUNVEGAN	FORT NELSON
		CRUISER	CRUISER	ST. JOHN	SHAFTESBURY	SHAFTESBURY	SHAFTESBURY		SIKANNI	LEPINE
				fish scales	fish scales	fish scales	fish scales	fish scales		

Stratigraphic terminology of early Upper Cretaceous rocks in parts of northeastern British Columbia and northwestern Alberta (modified from Stelck, 1950)

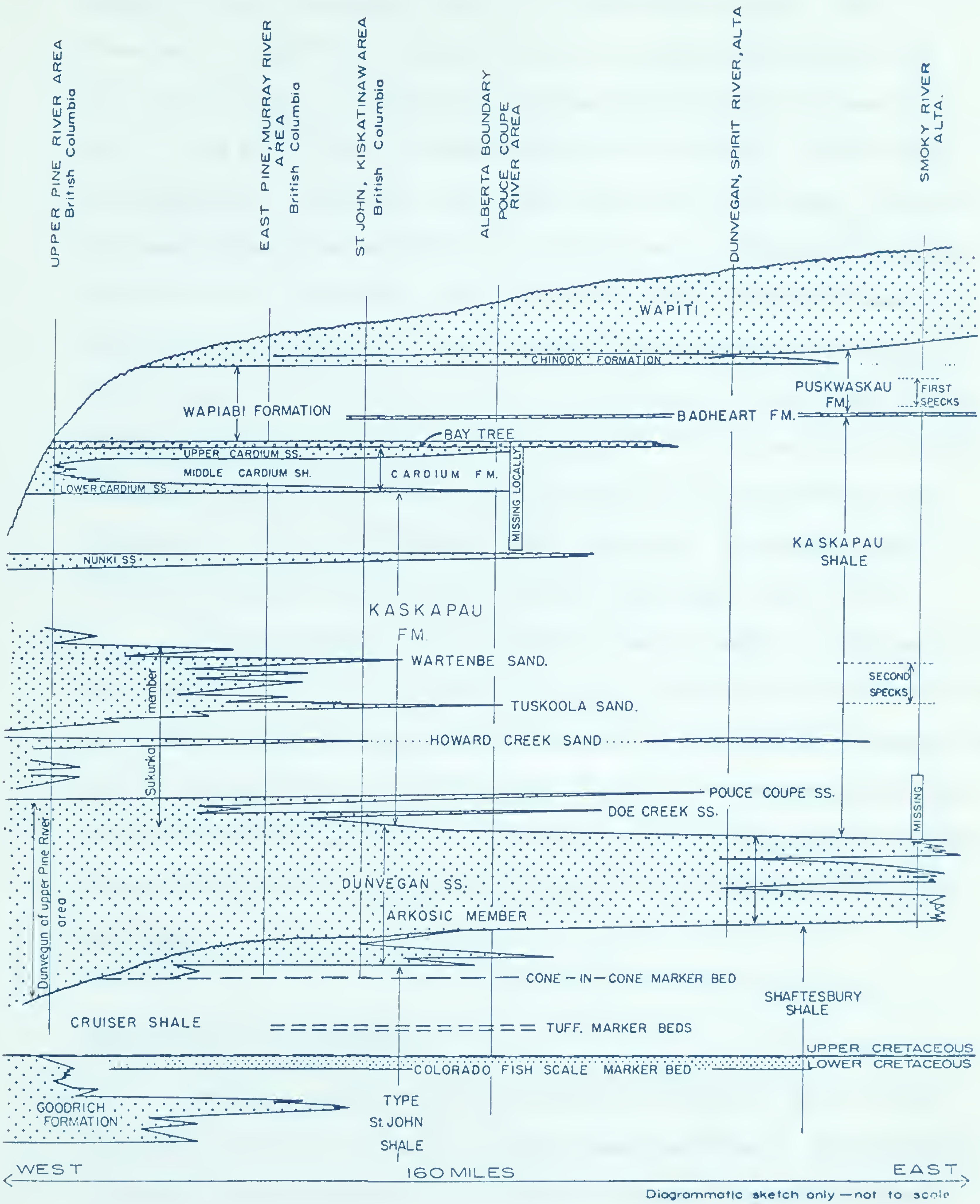


Figure 3. Schematic Diagram showing Facies Changes

uplands northwest and northeast of the town of Peace River (McLearn, 1945). In the valley of Smoky River, it occurs from Watino to near the confluence of this river with the Peace. Its occurrence is also reported in the valley of Pouce Coupe River, in Pine River Valley, on Kiskatinaw River, on Flat Creek, and in the valley of Moberly River. To the north, Hage (1944) traced the formation along, and east of, the Alaska Highway from near Dunvegan to Indian Creek. Southwest of Fort Nelson, on the north side of Tetsa Valley, M.Y. Williams (1944) considered the formation of conglomerate and sandstone on Table, Steamboat, and Teepee Mountains to be equivalent in age to the Dunvegan of the south. Far to the south the Dunvegan has been identified in Monkman Pass (McLearn and Henderson, 1944) and has been traced still farther south beyond Wapiti River, along the foothills of the Rocky Mountains by geologists of oil companies (McLearn, 1945). To the east, the formation is not recognized beyond the Athabasca River (Stelck, Wall, Wetter, 1948, p. 25).

The general geometry of the formation is that of a wedge. Its thickness varies from about 1200 feet in the west (Pine River section) to 300 feet in the east (east of type area). At the type area where only the arkosic member of the formation is thought to be exposed, the formation is over 400 ft. thick. Fig. 3 shows the decrease in thickness in the formation from west to east. The Pine River section includes in the sandy lithofacies an additional stratigraphic interval compared to the Dunvegan section of the type area.

Lower Contact of the Formation

The Dunvegan Formation overlies the marine Shaftesbury Formation and its equivalents and underlies the marine Kaskapau Formation (Table 1). Both boundaries are transitional and of brackish nature, and also diachronic. Regarding the lower boundary of the Dunvegan Formation, Stelck, Wall and Wetter (1958, p. 15) state --- "The top of the shaly St. John beds on Favels Creek (below East Pine, British Columbia), although still transitional, is as low as the cone-in-cone marker-bed (i.e., 61 feet

stratigraphically below the base of the Dunvegan Formation at Wilder Creek, or around 100 feet below the base at Beatton River) .... The total outcrop exposed at Dunvegan ferry-crossing (now a bridge crossing), that is, the type area, includes only the arkosic portion of the Dunvegan. The lower brackish member is assumed to be below water level at this point."

For their four fold division of the Dunvegan Formation at Beatton River section, Stelck et al. (1958) indicate that the lower members represent the sanding up of the Cruiser sea while the arkosic sand member introduces the fluvial phase and marks the expulsion of the sea from the St. John area. According to them, the arkosic member is known to rest in places with an erosional unconformity upon the brackish member in the area to the west and northwest where conglomerates become common.

In this connection Beveridge and Folinsbee (1956) have pointed out that this arkosic member (and hence most of the section at the type area) actually represents the unroofing of the batholiths in northern British Columbia. Based on evidence from palaeontology, Stelck and others (1958) have chosen the base of the arkosic member to mark the upper boundary of the Lower Cenomanian substage in this area.

Upper Contact of the Formation

The boundary of the Dunvegan Formation with that of the overlying Kaskapau Formation is also transitional and diachronic. Crickmay (1944) defined the top of the Dunvegan Formation at about the stratigraphic position of *Inoceramus dunveganensis*. However, because of the transitional nature of the boundary between the Dunvegan Formation and the Kaskapau Formation, the base of the latter formation is taken to mark the upper boundary of the Dunvegan Formation. At the type area of the Dunvegan Formation, the base of the Kaskapau Formation is usually placed at about 190 feet below the top of the Howard Creek sand (Stelck and Wall, 1955; p. 8). To the west, the base of the Kaskapau Formation on the Pine River near East Pine is often placed at the top of the Pouce Coupe snad member, as the latter is plant-bearing in that area

and contains thin coal seams. In the type area of the Kaskapau along the Smoky River in Alberta the basal stratigraphic portion is missing. Here the base of Kaskapau is about the same horizon as the top of the Howard Creek member. On the Pouce Coupe river, west of Bonanza, the basal beds are brackish and two clean sand members, the Doe Creek Sandstone (6 feet thick) and the Pouce Coupe Sandstone (30 feet thick), occur at 190 and 270 feet above the base respectively, and accordingly, the base of Kaskapau is placed 300 feet below the top of the Pouce Coupe sand member.

Age of the Dunvegan Formation

There is a general agreement that the boundary between the Upper Cretaceous and Lower Cretaceous series comes within the underlying Shaftesbury Shale or its equivalents. The *Ammobaculites pacalis* zone of the "Lower" Kaskapau (which includes Howard Creek sand) of Stelck and Wall (1955, p. 20) is considered latest Cenomanian, as two species of *Dunveganoceras* are found within the stratigraphic limits of this zone. Thus the Dunvegan Formation falls well within the boundaries of Cenomanian stage. Stelck, Wall and Wetter (1958, p. 7) further comment that the boundary between the upper and lower portions of the Cenomanian stage appears to fall within the Dunvegan Formation.

A continuous sequence of the local faunas for the Cenomanian stage from the Howard Creek sand member of the Kaskapau Formation to the fish-scale sand marker-bed of the Shaftesbury Formation is as follows (after Stelck *et al.*, 1958; Crickmay, 1944):

Upper Cenomanian:

Inoceramus aff. *fragilis* Hall and Meek

Dunveganoceras hagei Warren and Stelck

Dunveganoceras cf. *parvum* Cobban

Dunveganoceras albertense (Warren)

Dunveganoceras cf. *conditum* Haas

Ostrea aurea (Warren and Stelck)

Hillites cf. *septarianus* (Cragin)

Inoceramus dunveganensis McLearn)
)
Inoceramus rutherfordi Warren) Dunvegan Formation of the
) type area (C.R. Stelck,
Lower Cenomanian:) personal communication)
)
Brachidontes cf. *fulpensis* Stephenson)

Pleurobema dowlingi (McLearn)

P. cruiserensis n. sp.; *Brachidontes* cf. *tenuisculpta* (Whiteaves)

Beattonoceras beattonense Warren and Stelck

Irenicoceras bahani Warren and Stelck

"Fish-scale sands"

Regional Aspects

A natural lithologic division of the Cretaceous System is found in Europe where the lower clastic sequence of formations (Weald, Lower Greensand and Gault) make the Lower Cretaceous Series, and the overlying chalky beds (the Chalk) make the Upper Cretaceous Series. So far the boundary between Albian and Cenomanian is considered to mark the boundary between these two series, the base of Cenomanian is also the base of the Upper Greensand at the base of Chalk beds. Correlation of certain non-limy biofacies of the Cenomanian stage in other parts of the world with the type Cenomanian of the Chalk is rendered difficult because of the absence of such facies in the type section.

In North America, the boundary between Woodbine Formation and Washita Group, in the Gulf region, marks the boundary between Gulf Series and Comanche Series. Though for all practical purposes the Gulf Series is taken as equivalent to Upper Cretaceous Series, the base of Cenomanian is stratigraphically lower than the base of the Gulf Series.

It has been pointed out by McLearn (1945) that though all students of Canadian Cretaceous faunas accept an early Upper Cretaceous age for the Dunvegan Formation, no typical Cenomanian species or genus is present.

Stelck, et al. (1958) have suggested indirect correlation to define the Albian-Cenomanian boundary in western Canada in view of the endemic nature of the Lower Cenomanian faunas.

Marine beds of late Albian time are represented in western Canada by the lower member of Shaftesbury Formation or its equivalents. The Albian sea invaded this area from the north and it appears to have had its maximum southern expansion to the International Boundary in Saskatchewan (Wickenden, 1932). Recently it is assumed to have extended into the Williston Basin area of the United States (Stelck, et al., 1958) and around the area of Black Hills where it is represented by Mowry Shale (ibid, 1958), but from all published palaeontological evidence, it was not joined with the sea from the south continuously. This explains the difficulties of correlation with the Gulf region.

The top of the Albian beds, in western Canada plains, is marked with a wide-spread occurrence of a sand bed bearing fish scales. Inasmuch as the "fish-scale sand" represents conditions of slow deposition (Stelck, 1950), the supply of detritus by the close of Albian time was at a minimum. The microfaunal suite of this sand bed contains the pelagic foraminifera, Globigerina and Gumbelina (Stelck and Wall, 1955), which has been interpreted by Stelck et al. (1958) to represent possible connections with Atlantic Ocean, through Hudson's Bay (?).

The continuation of the deposition of marine shale at the beginning of Cenomanian time over most of the shales of Albian time and absence of calcareous benthonic foraminifera (Stelck, et al., 1958) are probably indicative of the return of normal deep water conditions. These conditions probably prevailed in the type area of Dunvegan Formation for most of the Lower Cenomanian substage as by late Lower Cenomanian time the detritus brought by the rivers created by the uplift to the west had begun to advance in this area as a delta front. According to Stelck and others (1958), this uplift occurred after the first Tuff marker-bed of the St. John Shale.

As the Lower Cenomanian substage came to a close, the area comprising the northeastern part of British Columbia and northwestern part of Alberta became a fresh water to submarine delta wedging into the Colorado sea to the east. Deltaic conditions probably continued till the early part of Upper Cenomanian substage after which there was a gradual deepening of water and marine shales (Kaskapau) were deposited. The deltaic sediments are referred to as the Dunvegan Formation.

CHAPTER THREE

TEXTURES

Grain-Size Analysis

General

The size-frequency distribution is a fundamental physical property of a clastic sedimentary rock. It may be considered as a direct expression of the physical conditions or the kinetic energy conditions within the environment of deposition. The grade scale most commonly used for expressing the grain size of sediments is the Wentworth scale. This is a geometric scale in that each grade limit is twice the value of the next smaller grade limit. An equivalent logarithmic scale, the Ø (phi) scale, devised by Krumbein (1936), is also frequently used in presenting data.

Twenty four sandstone samples from the Dunvegan Formation were analysed to determine: (1) size parameters and (2) sand, silt, and clay ratios.

Analytical Procedure

The size analyses were carried out by dry sieving the sand size-fraction (2 mm - 1/16 mm), and the silt/clay ratio was obtained by pipette analysis as described by Folk (1961). The following is a general outline of the procedure adopted:

Disaggregation: As all samples were relatively friable, they were passed through a jaw crusher and then disaggregated on a glass plate using a wooden roller. This was found to be a sufficiently gentle process to avoid grain breakage. No acid was used in the disaggregation process.

Sieving: Approximately 100 gms. of disaggregated sample was obtained using a Jone's type sample splitter. Eight-inch diameter Tyler screens of U.S. Standard mesh nos. 18, 35, 60, 80, 120, 140, 170, 200 and 230 were employed in the sieving.

For convenience, the sieving was done in two 15-minute stages on a Rotap, as all the screens could not be accommodated at one time. All sieve fractions were weighed to 0.01 gm. The pan fraction was kept for determining the silt/clay ratio by pipetting.

Pipette Analysis: The pipetting procedure followed for determining the clay percentage is as given by Folk (1961, p. 36) except that the dispersant used was 0.1 per cent Calgon solution, $Na_3(PO_4)_6$. Since the temperature of the solution varied from 28°C. to 29°C., the value for A in the formula

$$T\ (\text{min}) = \frac{\text{Depth in cm.}}{1500.A.d^2\ (\text{cm})}$$

was taken as 4.30. The time necessary for withdrawal at a depth of 10 cm for silt-clay boundary size (.0039 mm) was calculated to be 1 hour and 42 minutes. Separation of silt and clay fractions by this method depends on hydraulic values rather than dimensions, and is based on Stokes' formula, namely:

$$V = \frac{2gr^2\ (d_1 - d_2)}{9\ n}$$

in which g = attraction due to gravity

r = radius of particles

d_1 = density of the particles

d_2 = density of the fluid

n = viscosity of the fluid.

For this law to be true the particles must be spherical, but for natural sedimentary particles down to diameter 0.004 mm., the departure from spherical shape is not significantly large

Size Parameters

Size-frequency distributions are usually described in terms of such parameters, as: the mean and median, which are measures of the central tendency; the quartile deviation and standard deviation, which are measures of the variance or spread of the

distribution about the mean size; the skewness, which is a measure of the asymmetry of the distribution; and the kurtosis, which is a measure to compare the sorting in the central part with that in the 'tails' of the distribution. These parameters are here derived graphically from cumulative curves drawn from the weight-percentages of each size class obtained by sieve and pipette size-analysis methods (Table 2).

Measures of Central Tendency: Two measures of "average" particle size, mean and median were determined (Table 4).

The 'mean size' of a sediment may be determined in different ways. Here, the value used is the graphic mean (Mz) of Folk (1961) and is determined from the formula $Mz = (\phi16 + \phi50 + \phi84)/3$. This mean is considered to be somewhat better than Inman's (1952) formula $[(\phi16 + \phi84)/2]$, for the latter is less satisfactory in skewed curves.

The 'median' is also included in the table as it is a commonly used measure and also easier to determine than the mean. It is the value corresponding to the 50 percentile on the cumulative curve, and has been expressed here in ϕ units. This measure has the disadvantage of not being affected by the extremes of the curve. Table 4 shows that the ϕ values of Mz are always higher than those of the median, excepting sample H150, indicating that most sandstones have an excess of fine material.

Measures of Sorting: There are several measures that indicate the sorting or spread of the curve. Three different measures of sorting have been calculated here (Table 4):

(a) Trask's Sorting Coefficient, $So = \sqrt{(P75)/(P25)}$ (Trask, 1932)

(b) Graphic Standard Deviation $\sigma_G = (\phi84 - \phi16)/2$ (Inman, 1952)

(c) Inclusive Graphic Standard Deviation,

$$\sigma_I = (\phi84 - \phi16)/4 + (\phi95 - \phi5)/6.6 \quad \text{(Folk and Ward, 1957)}$$

According to Trask (1932), an So value of less than 2.5 indicates a well-sorted sediment, a value of about 3.0 is normal, and a value greater than 4.5 indicates

a poorly sorted sediment. These values were found later to be too high; Hough (1940) pointed out that most near-shore marine sand-size sediments have sorting coefficients between 1.0 and 2.0. Most beach sands have So = 1.3 - 1.5 (Folk, 1961; p. 44). The So value of the present samples might suggest that they are beach sands in contrast to their poorly sorted nature as shown by other sorting measures.

The graphic standard deviation σ_G (Inman, 1952), embraces the central 68 per cent of the distribution. If a sediment has σ_G equal to 0.5 ϕ, it means that 68 per cent of the grains fall within 1 ϕ unit centered on the mean (for a symmetrical curve), and indicates that the sediment is well sorted. The σ_G values (Table 4) for the Dunvegan sandstones are higher than 0.5 ϕ excepting samples 156 and 232, indicating that the sandstones are not as well sorted as the So values suggest.

The inclusive graphic standard deviation σ_I (Folk and Ward, 1957), covers 90 per cent of the distribution, and, as such, is still better measure of sorting. The following classification scale for sorting has been suggested (Folk, 1961):

σ_I under .35 ϕ, very well sorted
.35 - .50 ϕ, well sorted
.50 - 71 ϕ, moderately well sorted
.71 - 1.0 ϕ, moderately sorted
1.0 - 2.0 ϕ, poorly sorted
2.0 - 4.0 ϕ, very poorly sorted
over - 4.0 ϕ, extremely poorly sorted.

The σ_I values for the present samples range from 0.50 ϕ to 2.81 ϕ, though most samples have σ_I values between 1.0 ϕ and 2.0 ϕ. Hence, according to this scale, most Dunvegan sandstones are poorly sorted.

Out of the twenty four samples from a stratigraphical interval of about 390 feet, sample 156 is the best sorted and may have been deposited in a shoreline environment.

<u>Measures of Asymmetry</u>: Two different measures of the asymmetry or skewness of the cumulative curves of the sediments have been determined. These are:

(1) Graphic Skewness, $Sk_G = (\text{Ø}16 + \text{Ø}84 - 2\text{Ø}50)/(\text{Ø}84 - \text{Ø}16)$ (Inman, 1952)

and (2) Inclusive Graphic Skewness, Sk_I

$$= (\text{Ø}16 + \text{Ø}84 - 2\text{Ø}50)/2(\text{Ø}84 - \text{Ø}16)$$
$$+ (\text{Ø}95 + \text{Ø}5 - 2\text{Ø}50)/2(\text{Ø}95 - \text{Ø}5)$$ (Folk and Ward, 1957)

Sk_I has an advantage over Sk_G since the former covers 90 per cent of the curve while the latter considers only the central 68 per cent of the curve. Thus, Sk_I is more sensitive.

The skewness values obtained by the above formulae are pure numbers and are usually recorded with a plus or a minus sign. Symmetrical curves have Sk_G or Sk_I equal to zero. Sediments having excess fine material will have positive skewness and those with excess coarse material show negative skewness.

The following limits are suggested by Folk (1961):

Sk_I = + 1.00 to + .30 strongly fine-skewed

= + .30 to + .10 fine-skewed

= + .10 to - .10 near symmetrical

= - .10 to - .30 coarse skewed

= - .30 to - 1.00 strongly coarse-skewed.

The absolute mathematical limits of Sk_G and Sk_I are + 1.00 to - 1.00.

Sk_I is positive for all samples examined (Table 5). Sk_G is also positive except for samples H150 and 72. Most samples have Sk_I values greater than + .30. This means that most of the sandstones are strongly fine-skewed. Sample H150 has $Sk_I = 0.029$ which shows that this sandstone has a 'near symmetrical' curve.

A strongly fine-skewed cumulative curve coupled with a high kurtosis value (see p. 19) is suggestive of bimodality in the sediment (Folk and Ward, 1957; Spencer, 1963). The histograms of most samples (see Appendix) indicate bimodality to some

extent. Some cumulative curves also indicate bimodality, but, in most cases, it is probably hidden in the gentle curvature of the plot.

Measure of Kurtosis: In order to compare the sorting in the central portion to that in the 'tails' of the curve the kurtosis measure is used. The formula employed is that of graphic kurtosis, Kg (Folk and Ward, 1957) which is given as:

$$Kg = (\emptyset 95 - \emptyset 5)/2.44(\emptyset 75 - \emptyset 25)$$

For normal curves, Kg = 1.00. If the central portion is better sorted than tails, the curve is said to be leptokurtic, and platykurtic in the opposite case. The following limits have been suggested by Folk (1961):

Kg under 0.67, very platykurtic
0.67 - 0.90, platykurtic
0.90 - 1.11, mesokurtic
1.11 - 1.50, leptokurtic
1.50 - 3.00, very leptokurtic
over 3.00, extremely leptokurtic.

The absolute mathematical limits of this measure are from 0.41 to infinity.

In the samples studied, all (except sample H18 where Kg = 1.47) have Kg values over 1.50. Many samples have Kg values greater than 3.00, and in sample H133 it is over 8. This shows that the sandstones are very leptokurtic to extremely leptokurtic, and accordingly, the sorting in the 'tails' is relatively poorer. As suggested earlier (p. 18), the fine-skewed sediments have two modes, and near the finer mode sorting is poorer than near the coarser.

Scatter Plot of Size Parameters

Mean size, standard deviation (sorting), skewness and kurtosis are plotted against each other in turn as scatter diagram (p. 20). The plots show no obvious relationships between the parameters; for example, any decrease or increase in mean size does not correlate with corresponding changes in sorting, etc. However, it is noted that the plots

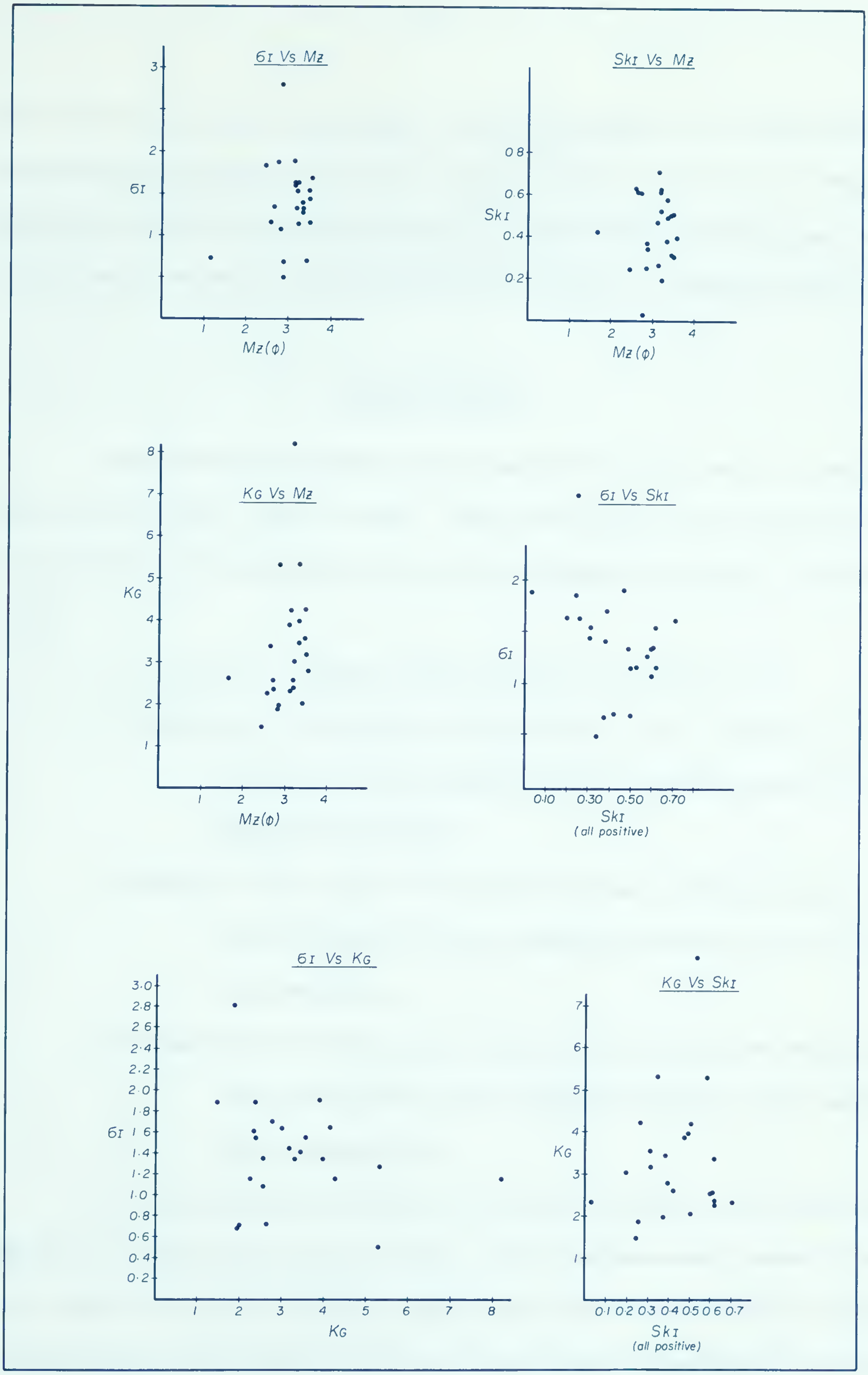


Figure 4. Scatter Plot of Size Parameters

fall in the same quadrant of the graph. This might suggest that the depositional environment of the entire section was virtually the same, and that the changes in the magnitude of the size parameters are more or less a reflection of the proportions of two modal sizes of sediments supplied and of minor shifting of the shoreline of the inland sea.

Textural Maturity

The maturity of a sediment may be defined in textural terms as well as compositional terms (Pettijoh, 1957, p. 522). Folk (1951) defined textural maturity as a measure of the stability of the deposition site and input of modifying energy. He recognized four stages:

(1) Immature:- Sediment contains more than 5 per cent clay

(2) Submature:- Clay content is less than 5 per cent; size range encompasses more than 1 Ø unit between the 16th and 84th percentile of total grain size distribution.

(3) Mature:- Clay content is less than 5 per cent and size range is less than 1 Ø unit between the 16th and 84th percentile of the total grain size distribution.

(4) Supermature:- Clay content is less than 5 per cent; size range is less than 1 Ø unit between the 16th and 84th percentile; roundness of quartz grains exceeds 0.35.

No time sequence is intended in the textural maturity scale because rapid changes in sorting govern textural maturity. The complete range is known to occur under rapidly changing conditions in modern environments (Folk, 1956). However, the last stage suggests prolonged transport and characterizes mineralogically mature sands such as certain beach sands.

The sandstones under study fall in the immature and submature stages of the above scale (Table 3).

Grain Size Nomenclature

Clastic sedimentary rocks are known to have extreme variation in composition and in grain size. A separate grain size description independent of mineral composition is always helpful in the study of sedimentation. The writer has adopted Folk's (1954) scheme for textural classification of the Dunvegan samples (Figure 5). Most samples according to this nomenclature are silty sandstones. However, a few of them also fall in the 'sandstone' and 'muddy sandstone' groups.

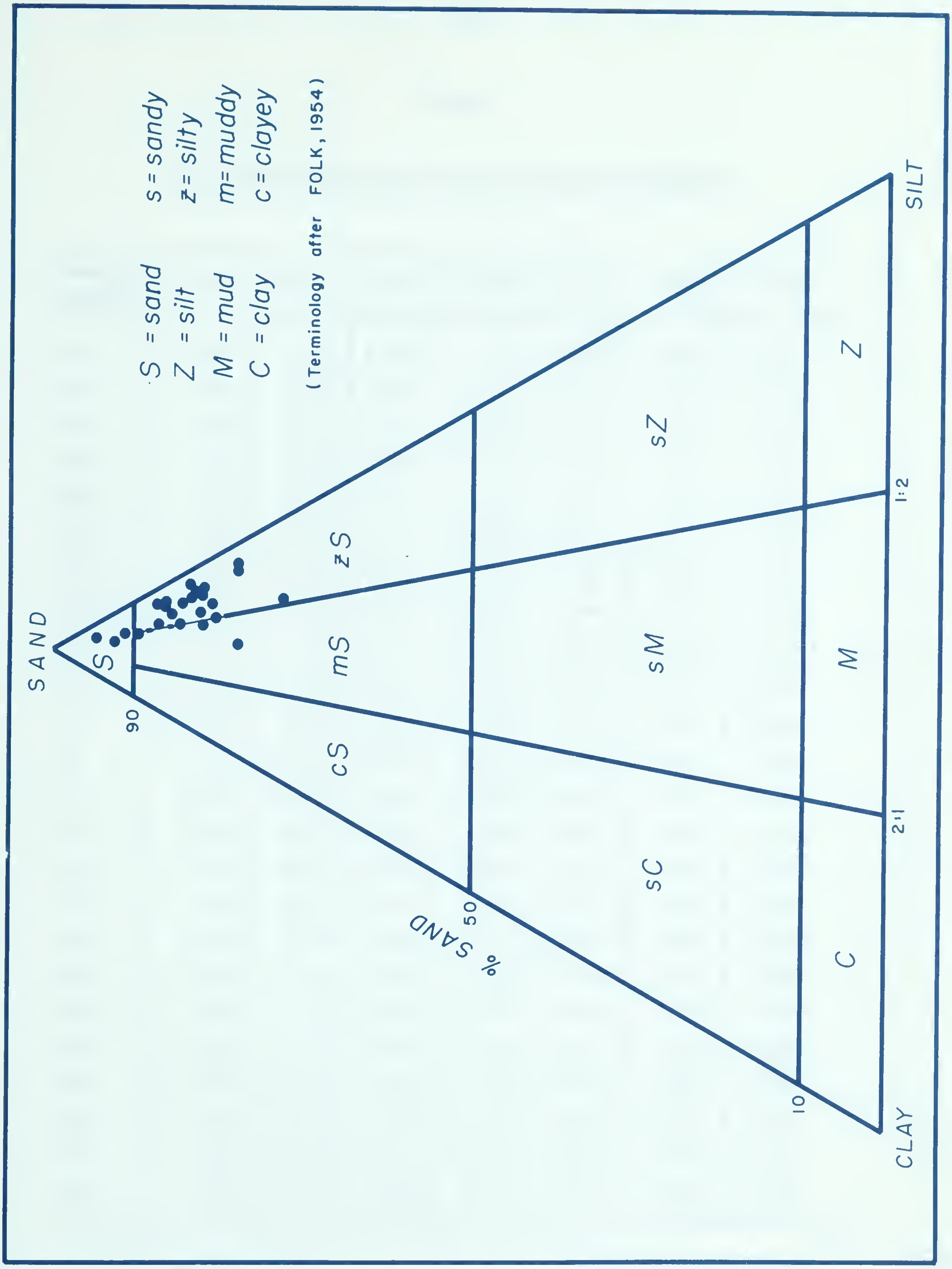


Figure 5. Grain Size Nomenclature of Sandstones

Table 2

Data* from Cumulative Curves of Dunvegan Sandstones

Sample number	Ø5	Ø16	Ø25	Ø50	Ø75	Ø84	Ø95
H6	0.55	1.20	1.35	1.55	1.85	2.20	3.75
H18	0.25	0.93	1.35	2.35	3.30	4.05	7.25
H30	1.57	2.02	2.12	2.40	2.90	3.50	8.00
H48	1.40	2.68	3.05	3.37	3.90	4.45	8.00
H58	1.60	2.69	2.91	3.10	3.57	4.20	8.00
H88	2.00	3.05	3.15	3.33	3.72	4.10	7.90
H133	1.50	2.80	2.95	3.02	3.25	3.80	7.50
H150	0.24	1.12	2.15	2.95	3.45	4.13	7.70
12	0.75	2.40	2.75	3.10	3.55	3.95	9.00
37	0.75	2.30	2.70	3.20	3.75	4.15	8.50
39	1.00	2.30	2.50	2.90	3.50	4.15	10.50
66	1.10	2.70	3.05	3.35	3.90	4.40	8.50
72	0.25	0.75	1.30	2.90	3.85	4.90	12.00
86	2.50	3.10	3.15	3.30	3.50	3.85	6.00
96	2.10	2.42	2.55	2.80	3.15	3.40	5.00
117	1.50	2.67	2.92	3.20	3.75	4.10	8.50
144	2.00	2.85	3.00	3.13	3.50	4.00	8.50
156	2.40	2.66	2.75	2.87	2.95	3.10	5.00
169	1.80	1.95	2.06	2.35	3.00	3.46	7.00
183	2.10	2.37	2.47	2.88	3.65	4.35	9.00
188	2.05	2.47	2.65	2.90	3.60	4.25	8.00
232	1.60	1.97	2.11	2.42	3.05	3.75	7.50
237	1.80	2.03	2.16	2.50	3.20	4.90	7.70
244	1.50	2.55	3.00	3.35	4.10	4.80	9.00

* Values are given in Ø

Table 3

Clay Percentage, Sorting (σ_I) and Textural Maturity

Sample number	Percentage of Clay	Sorting (σ_I)	Textural Maturity
H6	1.02	0.734	Sub mature
H18	3.06	1.840	" "
H30	4.44	1.344	" "
H48	4.93	1.442	" "
H58	4.05	1.347	" "
H88	4.49	1.156	" "
H133	3.73	1.159	" "
H150	4.30	1.88	" "
12	5.02	1.637	Immature
37	5.17	1.636	"
39	6.98	1.901	"
66	5.15	1.546	"
72	11.74	2.817	"
86	3.75	0.717	Sub mature
96	3.12	0.684	" "
117	5.27	1.418	Immature
144	5.40	1.272	"
156	3.01	0.503	Sub mature
169	3.84	1.165	" "
183	6.68	1.540	Immature
188	5.12	1.346	"
232	3.54	1.088	Sub mature
237	4.11	1.611	" "
244	5.82	1.698	Immature

Table 4

Statistical Parameters of Average Size and Sorting

Sample number	Average Size *		Sorting		
	Median (Ø50)	Graphic Mean (Mz)	S_o	σ_G	σ_I
H6	1.55	1.65Ø	1.170	0.500	0.734
H18	2.35	2.44Ø	1.563	1.560	1.840
H30	2.40	2.64Ø	1.169	0.740	1.344
H48	3.37	3.50	1.130	0.885	1.442
H58	3.10	3.33	1.107	0.755	1.347
H88	3.33	3.49	1.086	0.525	1.156
H133	3.02	3.20	1.049	0.500	1.159
H150	2.95	2.73	1.266	1.505	1.880
12	3.10Ø	3.15Ø	1.135	0.775	1.637
37	3.20Ø	3.21Ø	1.178	0.925	1.636
39	2.90Ø	3.11Ø	1.183	0.925	1.901
66	3.35Ø	3.48Ø	1.173	0.850	1.546
72	2.90Ø	2.85Ø	1.720	2.075	2.817
86	3.30	3.41Ø	1.054	0.375	0.717
96	2.80	2.87Ø	1.111	0.490	0.684
117	3.20	3.32Ø	1.133	0.715	1.418
144	3.13	3.32Ø	1.079	0.575	1.272
156	2.87	2.87Ø	1.035	0.220	0.503
169	2.35	2.58	1.206	0.755	1.165
183	2.88	3.20	1.215	0.990	1.540
188	2.90	3.20	1.165	0.890	1.346
232	2.42	2.71	1.202	0.390	1.088
237	2.50	3.14	1.217	1.435	1.611
244	2.35	3.56	1.168	1.125	1.698

*values are given in Ø

Table 5

Statistical Parameters of Skewness and Kurtosis

Sample number	Skewness*		Kurtosis
	Sk_G	Sk_I	K_G
H6	0.300	0.422	2.622
H18	0.089	0.244	1.471
H30	0.486	0.613	3.378
H48	0.220	0.311	3.182
H58	0.456	0.493	3.974
H88	0.466	0.507	4.242
H133	0.560	0.526	8.196
H150	-0.215	+0.029	2.351
12	0.096	0.263	4.226
37	0.027	0.197	3.024
39	0.351	0.475	3.893
66	0.235	0.313	3.567
72	-0.036	+0.256	1.888
86	0.466	0.504	2.049
96	0.224	0.370	1.980
117	0.258	0.386	3.456
144	0.513	0.582	5.327
156	0.045	0.341	5.327
169	0.470	0.629	2.267
183	0.484	0.628	2.396
188	0.516	0.615	2.566
232	0.494	0.608	2.572
237	0.672	0.717	2.325
244	0.288	0.379	2.794

* All positive values unless otherwise indicated

CHAPTER FOUR

COMPOSITION

Heavy Minerals

Separation

Heavy minerals are defined operationally as those with a specific gravity greater than 2.85, the approximate specific gravity of the liquids used to separate them from lighter quartz, feldspar, or calcite. In the present study, the liquid used to separate the 'heavy minerals' was tetrabromoethane ($CHBr_3.CHBr_3$) having a specific gravity of 2.9.

The sieve fractions from 0.25 to 0.0625 mm., obtained during the size analysis were utilized for the separation of heavy minerals. To remove argillaceous coatings the sieve fractions were mixed into one sample and allowed to stand in water for about an hour. They were then treated with an electric mixer for about 5 minutes and decanted until the clay was washed out. The grains were dried in an oven at 110°C temperature and placed in a standard separating funnel containing tetra-bromoethane for separation. The separated heavy minerals were washed with acetone and weighed.

Method of Study

The heavy mineral grains were mounted in aroclor (refractive index = 1.67) on a 1 mm. graticule slide. They can be divided into two groups: (a) opaques and (b) non-opaques. About 200 non-opaque grains from each slide were identified; a count was kept of the opaque grains that were encountered, but no attempt to identify them was made, as they probably have little genetic significance (Mellon, 1956, p. 31). Micas were also excluded from the count.

Fifteen non-opaque mineral species were identified. The most common minerals are: garnet, apatite, zircon and tourmaline. Staurolite is fairly common but not present in all slides. Pyroxenes and amphiboles (except glaucophane) are absent from the suites. The percentages of identified 'heavies' are shown in table 6.

Descriptions of Heavy Minerals

Apatite

This mineral is abundant. In general, the percentage varies from 20 to 40, ranging from 12 per cent to as much as 50 per cent of the non-opaque suite.

The grains are subangular to rounded, slender prisms to stubby anhedra, and colorless. Inclusions are generally present. They are globular to dusty and show, not infrequently, a distribution parallel to the c-axis.

The relative persistence charts of Smithson (1941) and Pettijohn (1957) show apatite as a stable mineral. However, from his experimental studies on a group of minerals, Thiel (1940) concluded that apatite is least resistant to abrasion and also the most soluble in the group. The mineral seems to be very sensitive to the chemistry of the environment; it is stable under alkaline conditions, whereas in acid solutions it is relatively soluble. Apatite could lose its angularity during a relatively short distance of transport. Much of the subangular apatite may be of first cycle origin (probably igneous), whereas the more rounded grains may be derived from pre-existing sedimentary rocks. However, in the latter event, the mineral would require persistence through two periods of weathering. Such a situation would imply relatively rapid erosion as apatite is easily decomposed in weathered rocks (Smithson, 1941). An alternative to this is that the source areas had limited amounts of the humus materials which account for most of the acidity of soil waters (Lerbekmo, 1962).

Chloritoid

This mineral is rare in all samples except in the upper two (232 and 244) where it is more abundant than any other heavy detrital mineral.

Chloritoid occurs as greenish-blue, very weak to non-pleochroic flakes full of tiny, oval or rounded, black, opaque inclusions which are sometimes so abundant that the mineral is nearly opaque. The mineral can be confused with certain varieties of chlorite, except that the refractive index of chloritoid is much higher. The grains always show some signs of rounding; most commonly they are classed as subrounded. Chloritoid is known to have its source in low to medium rank metamorphic rocks.

Garnet

Garnet is one of the most abundant heavy minerals in the Dunvegan sandstones. The only other heavy mineral that compares with it in abundance is apatite.

It occurs in three color varieties: (i) brown, (ii) pink and (iii) colorless. Intermediate colors between brown and pink are difficult to categorize, and therefore are included with colorless garnets. The brown garnets are predominant.

Euhedral garnet grains are fairly common; they show dodecahedral crystal faces, usually with six-sided outlines. Subconchoidal to conchoidal fracturing is very common, especially in anhedral grains. The grains seem to be mainly equidimensional, and most of them fall between 0.1 mm to 0.15 mm in size. The grains are usually angular to subangular and occasionally subrounded. From their angularity, the majority of the garnets appear to be first cycle.

Inclusions are present in all three types of garnet; they are globular to dusty, often opaque, and vary in abundance.

Effects of corrosion are occasionally observed on the surfaces of garnet grains. However, instances of truly etched grains with 'micro-scaly' appearance

are rare. A few grains have been corroded to form a "skeleton crystal" (Smithson, 1941, p. 100) with a rhombic dodecahedral structure. Such features are probably due to lack of stability of garnet in alkaline intrastratal solutions.

Glaucophane

This is the only amphibole observed, being present in a few slides (Table 6). It has a short stumpy habit and is present only in trace quantities. It is usually subangular to subrounded with fairly distinct (110) cleavage.

Sphene

This mineral forms up to 3 per cent of the non-opaque grains in some samples. It usually has a pale yellowish-brown color with very weak pleochroism; the grains commonly show lack of extinction. Sphene generally occurs as subangular, subhedral to euhedral grains.

Staurolite

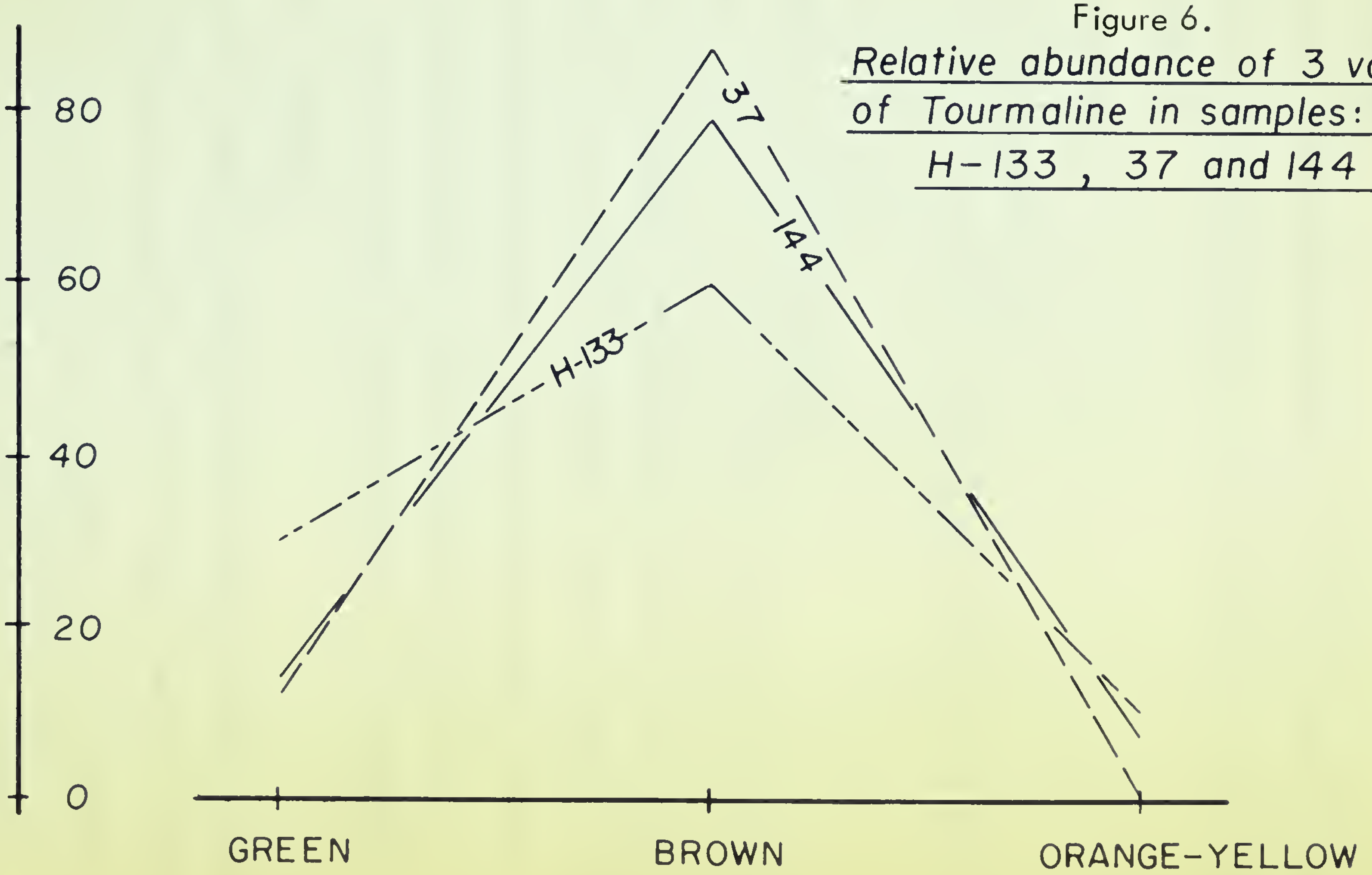
Staurolite is found to be present in most slides but the highest percentage recorded is four; in some samples it was not observed at all. Many grains show saw tooth solution terminations and often have quartz inclusions.

Tourmaline

Tourmaline is present in all the samples but is not a dominant mineral, the quantity varying from less than 1 to 13 per cent.

Various varieties of colored tourmaline were grouped into three varieties: brown, green, and yellow. These three varieties are present in most samples although pink and blue varieties were also observed. In three samples, the three varieties have been compared on a graph (figure 6), from which it can be seen that the brown variety is most prevalent.

Figure 6.
Relative abundance of 3 varieties of Tourmaline in samples: Nos. H-133 , 37 and 144



Tourmaline is found as subangular to well-rounded grains but most commonly is subangular and subrounded. It is very often prismatic but stubby grains are equally common. Inclusions, which normally are present, are globular and dusty, commonly opaque, and vary in abundance. Some grains are so full of opaque inclusions that the identity of the grain is nearly obscured. In general, it can be said that brown grains are more prone to inclusions.

The occurrence and significance of tourmaline as a detrital mineral has been discussed by Krynine (1946), who outlined five main sources of sedimentary tourmaline:

(1) Granitic tourmaline;

(2) Pegmatitic tourmaline;

(3) Tourmaline from metamorphic rocks;

(4) Sedimentary authigenic tourmaline, occurring as colorless overgrowths on detrital tourmaline grains;

(5) Reworked tourmaline from older sediments.

The first four sources include the various varieties of primary tourmaline which upon the erosion of the parent rock appear in sediments as first-cycle detrital grains. Whereas authigenic tourmaline is usually easily recognized, granitic, pegmatitic and metamorphic tourmaline must be differentiated on the basis of color and inclusions (Krynine, 1940, 1946). Reworked tourmaline is derived from the erosion of pre-existing sedimentary rocks, and must be differentiated from igneous or metamorphic varieties on the basis of grain morphology.

Although just how well rounded a tourmaline grain must be to justify calling it second-cycle is a matter of debate, examination of the Dunvegan samples indicates that at least 10 per cent of the tourmaline grains are sufficiently well rounded to be classified as second-cycle. But, if the morphology of apatite is any indication to relatively brief transport, much more than 10 per cent of tourmaline might have been

derived from pre-existing sedimentary rocks in view of its stability and chemically inert character. The remaining 90 per cent of the grains, which vary from small idiomorphic crystals or angular fragments of larger crystals to subangular or subrounded grains, might be taken as first-cycle, contributed by some igneous and metamorphic sources which supplied other first-cycle minerals in the suite.

According to Krynine (1946) the color varieties observed suggest the following possible sources: (a) brown and green - plutonic bedrock, (b) yellow - injected terrane, and (c) pink and blue - pegmatites.

Zircon

The zircons are divided into two types based on their texture: (1) subangular to angular or euhedral, and (2) subrounded to well rounded or subhedral to anhedral. The first type is usually colorless, mostly prismatic, with numerous inclusions and often finely zoned. Some of the prismatic zircons show pale yellow colour. Many of the well-rounded zircons have a distinctive pale pink to purple color and are referred to as rounded "hyacinth" zircons. The first type may be the product of the first cycle of erosion, whereas most zircons of the second type probaboy have undergone several cycles of erosion.

The crystals of most euhedral zircons have bipyramidal terminations: (111), (331), etc. Some euhedrons have pyramidal termination at one end only, the other end being a slightly rounded fracture. The maximum length of a bipyramidal zircon (sample H6) recorded is 0.4 mm with a breadth of 0.06 mm. Euhedral zircons with length-breadth ratios of about 1.5 and dipyramidal terminations are also present. Rare instances of twinned zircons were also observed.

Zoning in the zircons is fairly common. In euhedral cyrstals it ranges from single overgrowths over euhedra to several thin parallel zones enclosing an unzoned central area. Euhedral overgrowths on rounded and etched zircon grains

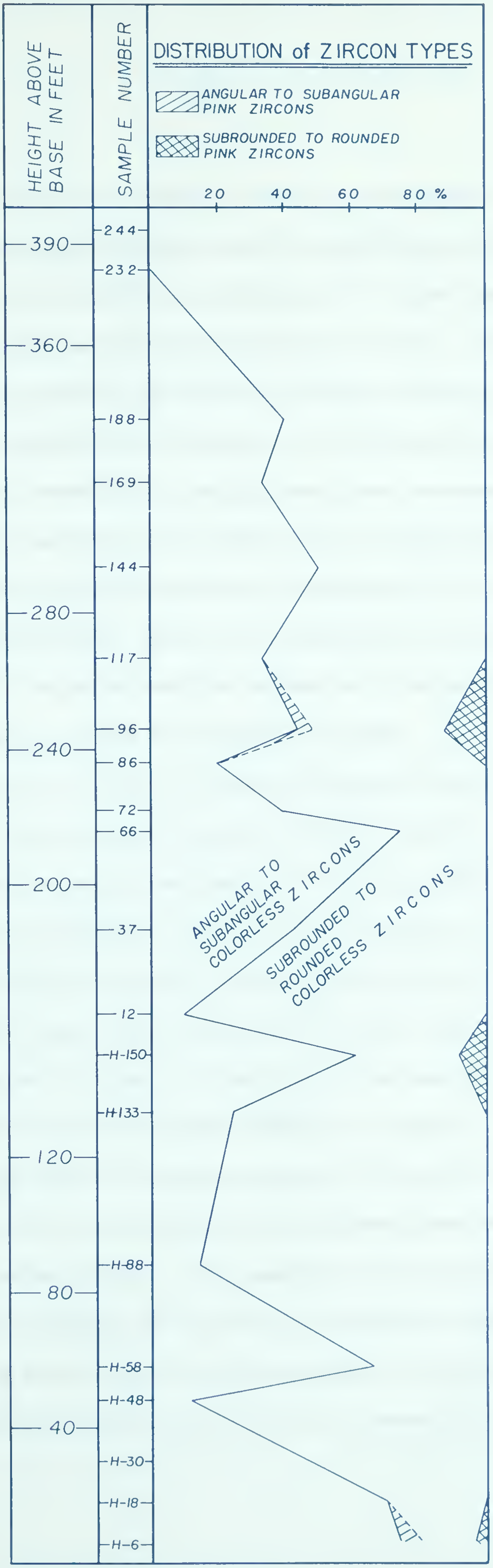

HEIGHT ABOVE BASE IN FEET
SAMPLE NUMBER
DISTRIBUTION of ZIRCON TYPES
ANGULAR TO SUBANGULAR PINK ZIRCONS
SUBROUNDED TO ROUNDED PINK ZIRCONS
20
40
60
80 %
390
360
280
240
200
120
80
40
244
232
188
169
144
117
96
86
72
66
37
12
H-150
H-133
H-88
H-58
H-48
H-30
H-18
H-6
ANGULAR TO SUBANGULAR COLORLESS ZIRCONS
SUBROUNDED TO ROUNDED COLORLESS ZIRCONS

Figure 7.

was recorded in a few cases. Poldervaart (1956, p. 546-548) in a review of crystallization of zircon in granite magma noted that morphological uniformity of zircons (i.e., uniformity in crystal habit and elongation) in a single igneous body is the most convincing evidence for early crystallization of zircon. Also, the predominance of euhedra and the occurrence of zircon as inclusions in early as well as late constituent minerals suggest that zircon begins to crystallize early in the history of a magma. However, crystallization probably takes place in several stages, as shown by zoned zircons, overgrowths over euhedra, and corroded grains. The coexistence of corroded and sharply euhedral crystals may be explained by fluctuations in temperature of the magma (Spotts, 1962). Some of the rounded grains represent early formed grains that were partially reabsorbed when the temperature of the magma was increased, and the euhedral ones were formed during subsequent cooling.

Inclusions are of different shapes and sizes; most common are rod-shaped and globular ones. Many colorless zircons carry abudant inclusions. A few euhedral zircons possess only one rod-shaped apatite (?) inclusion parallel to the c-axis and covering the entire length of the prism. In many instances the inclusions are aligned parallel to the length of the crystal, but just as frequently there is no particular orientation. Black opaque mineral inclusions of unknown identity are also present.

Outgrowths on zircons were observed in a few cases (see pl. 2). According to Poldervaart and Eckelmann (1955), an outgrowth is a protruberance of variable size which forms on the parent euhedron in any position. It is probably that the outgrowths on zircon were formed in the sandstones subsequently to deposition as suggested by Butterfield (1936). The composition of the outgrowths is not known, but, as Smithson (1941) suggested, if it is zircon, it is necessary to assume that some zirconium-bearing mineral has suffered decomposition and that zircon has crystallized at a temperature much lower than that at which it is normally formed.

The euhedral zircons are suggestive of an igneous source. Spotts (1962) in his study of Coast Range batholiths concluded that the zircon in gabbro and in mafic zenoliths in the quartz diorite suite is predominantly anhedral in contrast to predominantly euhedral forms in granite and quartz diorite. He attributed this difference to late and early crystallization of the mineral, respectively. The rounded grains are probably indicative of reworked sediments, though it is realized that rounding might also be imparted to the grain by fluctuation in temperature of the magma. The well-rounded hyacinth zircons indicate several cycles of erosion. Regarding the age of hyacinth variety of zircon, Tomita (1954) believes it to be Precambrian or early Palaeozoic.

Others

Here are included rutile, brookite, anatase, kyanite, zoisite and epidote. These minerals have been observed in several slides but only in trace quantities. Most of these minerals always show some degree of rounding. One or two well-formed prismatic grains of rutile with pyramidal terminations and reddish-brown colour are present. A few brookite grains were recorded in some slides but their identification could possibly be confused with sphene as both commonly show lack of extinction. Anatase, kyanite, zoisite and epidote are extremely rare and occur in only a few samples; their numbers hardly exceed one grain per slide.

Micaceous Minerals

Chlorite, biotite, and occasionally muscovite, have been encountered in most samples; however, since their quantities are largely a function of sorting, their percentages have not been included with the other non-opaque minerals.

Opaques

The different types of opaque minerals were not discriminated. The total number of opaque grains per hundred of non-opaque grains in each slide is shown in table 6.

Table 6 Percentages of heavy minerals in Dunvegan sandstones

	H6	H18	H30	H48	H58	H88	H133	H150	12	57	66	72	86	96	117	144	169	188	232	244
Anatase	-	-	-	-	-	-	-	t	-	1	-	-	1	-	-	-	-	-	-	-
Apatite	15	16	12	47	24	58	41	20	32	34	35	40	22	19	37	45	24	48	3	2
Brookite	t	-	-	-	-	-	-	-	1	-	-	1	-	-	-	-	-	-	-	-
Chloritoid	t	t	t	t	t	-	-	t	-	1	2	1	5	-	-	t	1	2	72	78
Epidote	t	-	-	-	-	t	-	-	-	-	-	1	1	-	-	-	-	-	-	-
Garnet	52	59	67	30	54	30	43	60	50	39	40	33	54	46	51	34	54	28	6	5
Glaucophane	-	-	t	t	-	t	t	-	-	1	-	-	1	-	-	-	-	-	-	-
Kyanite	-	-	-	t	-	-	t	t	-	-	t	-	1	-	-	-	-	-	-	-
Monazite	t	-	-	-	-	-	-	-	-	-	-	1	-	t	1	-	2	2	-	-
Rutile	t	3	2	2	t	1	-	-	1	-	1	2	-	1	2	-	-	-	2	-
Sphene	t	-	t	-	-	-	-	-	2	-	-	5	-	t	1	t	7	3	-	-
Staurolite	7	t	3	-	t	-	3	t	3	-	t	1	4	1	2	2	6	5	-	-
Tourmaline	t	5	3	6	7	6	8	2	8	17	7	8	6	1	2	13	2	6	8	7
Zircon	23	14	10	12	11	4	3	13	3	7	13	7	5	30	3	4	3	5	9	8
Zoisite	-	-	-	-	-	-	-	t	-	-	-	-	-	-	1	-	1	-	-	-
Opaques	254	151	168	215	170	127	146	131	114	243	216	218	118	172	169	121	115	94	121	108

N.B. 't' = less than 1%; '-' = absence.

Petrography

General Statement

The Dunvegan sandstones are light grey, generally medium-grained and friable. The sandstones do not show any significant change on weathering. Microscopic study was carried out on 15 of the 24 samples. The fine-grained sandstones and several closely spaced specimens were excluded from this study. The slides were mounted on a mechanical stage, and each grain was examined and recorded. Depending upon the grain size, a slide would contain anything between 400 to 600 grains. The average detrital composition of the sandstones is: quartz, 45 per cent; feldspar, 10 per cent; rock fragments (chert, siltstone, argillite, etc.), 45 per cent. Detailed descriptions of these components are given below.

Quartz

Quartz varies in quantity from about 30 to 53 per cent (Table 7). The grains are angular to subangular and fairly well sorted. Two main varieties are recognized based on their morphology and general appearance under the microscope. They are referred to here as 'common quartz' and 'composite quartz'.

Common quartz occurs as single grains and includes all quartz grains which appear essentially free of any recrystallization effect. These grains are further characterized by near absence (less than 5°) of undulatory extinction. This limit was chosen arbitrarily for the sake of convenience, and no genetic relationship is suggested. Most quartz grains belonging to this group have regular to irregular boundaries, and are subsequent, but a few show straight edges. They usually have a few show straight edges. They usually have a few inclusions.

Generally speaking, this group includes most of Folk's (1961) igneous quartz, volcanic quartz and part of his vein quartz. To a large extent, this quartz probably

represents igneous (e.g., plutonic, volcanic, vein, etc.) and sedimentary sources. Quantitative study of the various kinds has not been undertaken, though many such genetically significant varieties are present.

The other variety called "composite" quartz is chiefly polygranular. It is characterized by a mosaic of more or less equidimensional grains with or without inter-quartz mica flakes. Whenever such mica flakes occur, the quartz grains are somewhat elongated with parallel edges, a feature characteristic of Folk's (1961) schistose quartz. However, such grains are rare. The predominant quartz type within this variety is one which compares very closely with Folk's "recrystallized metamorphic quartz".

This variety of quartz has subangular to subrounded outlines with 2 to 10 sub-individuals forming the grain. The extinction of the composite quartz individuals may be straight to undulatory, and a few single grains with undulatory extinction greater than 5 degrees have also been included with this variety. The grains may or may not have inclusions, and boundaries may be straight to crenulated. The grains are, however, devoid of any secondary authigenic growths and may be considered, generally, as metaquartzite fragments. It is also possible that, in part, they represent reworked grains.

The quartz grains in the Dunvegan Formation are possibly derived from all three major types of source rocks: igneous, metamorphic and sedimentary. It is always difficult to determine the amount which any source might have contributed, but from the presence of other minerals, it is suggested that igneous and sedimentary rocks were the main contributors.

Feldspar

The quantity of feldspar in the samples ranges from 1 to 18 per cent (Table 7) and consists of both potash feldspar and plagioclase.

Potash feldspar: Potash feldspar is represented by orthoclase and sanidine. The ratio between these two mineral species varies considerably from sample to sample and has not been determined accurately, but probably averages about 1:1.

Sanidine is usually very clear, occasionally with euhedral to subhedral outlines. Orthoclase is very often cloudy, generally along the cleavage planes. According to rough estimation, sanidine shows 2V values up to 10 degrees, whereas orthoclase has 2V values of 65° to 70°, approximately. Microcline is absent except in sample H6 where a single grain was recorded.

It is not known how much of the orthoclase is present as adularia. Feldspars are generally taken to represent an igneous source, but some adularia may come from low grade metamorphic rocks. Sanidine is a high temperature potash feldspar derived from a volcanic source. The sanidine may have been derived from a contemporaneous volcanic source, or it may have been contributed by any pre-existing rock of this nature.

Plagioclase: Plagioclase is present in small quantities in most samples, but in a few it is completely absent. The refractive indices of this mineral were measured by immersing the mineral grains in various liquids of known index. The indices obtained fall constantly between 1.536 and 1.544 which indicates oligoclase of composition close to $An_{20}Ab_{80}$. The extinction angle observed in these mineral fragments (which consist, in large part, of 001 and 010 cleavage plates) was small (1 degree to 6 degrees). This plagioclase was probably derived either from a persilicic igneous rock or a metamorphic rock. No basic or ultrabasic feldspars were observed.

Rock fragments

Rock fragments include chert, volcanic fragments, argillaceous rock fragments and other grains which appear basically to be an aggregate of different mineral grains. They make up from 32 to 58 per cent of the sandstones (table 8).

Chert: Chert constitutes a major part of the rock fragments. It is present in all the samples but is most abundant in the basal sandstone (table 8). Most chert grains under reflected light appear dull grey to dark; others are dark brown-black to completely black. The colors are not found to have any specific relation to the thin section characteristics described below.

Many different textural varieties of chert were observed. It is not known whether these have any genetic significance. The following varieties have been observed:

(1) Grains having equidimensional subindividuals. In this group, two types can be further recognized: (a) subindividuals with any dimension less than 5 microns and (b) those larger than 5 microns but less than 20 microns is recognized as megaquartz, whereas one of less than 20 microns is micro quartz. Chert consists essentially of micro quartz.

(2) Grains with non-equidimensional subindividuals. This group shows heterogeneity in the size of subindividuals. Here are included: (a) Chert grains with subindividuals ranging in size from 0 to 20 microns; (b) grains which have a few subindividuals more than 20 microns. When such subindividuals (more than 20 microns) dominate, the grain may be called microquartzite. However, no separate group of microquartzite has been established here as such grains are rare. (c) Grains showing chalcedony which is observed as fibrous bundles. Some chert grains containing chalcedonic quartz contain fossil structures. However, no attempt has been made to determine the nature of these, because of their very infrequent appearance in the slides.

In conclusion, the order of abundance of the above chert varieties is as follows: 1(a), most abundant; 1(b), abundant; 2(a), common; 2(b), rare; and 2(c), very rare.

The high percentage of chert strongly suggests that a sedimentary source was a major contributor to sedimentation.

Volcanic rock fragments: These constitute a minor percentage of the rocks, being present in only a few samples. However, in the basal sample (No. H6), they make up to 4 per cent of the total detrital grains. These grains are made up usually of a felted mass of tiny lath-like feldspar crystals, occasionally with some ferromagnesian minerals. In general, they have a pale yellow-brown color in transmitted light.

In some cases their identity is confused with other rock fragments, especially silicified argillaceous rock fragments. In such cases, the author has tended not to record them as volcanic.

Carbonate rock fragments: Sand-size fragments of carbonate rock are absent from all slides except the upper two (Nos. 232 and 244). Number 232 is a medium-grained sandstone, and, has over 10 per cent of detrital carbonate rock(s) grains. Number 244 is a fine-grained sandstone and for that reason was not included in the quantitative study. However, a rough estimate of content of carbonate rock fragments was found to be around four per cent.

Introduction of these carbonate fragments suggests that carbonate rocks were suddenly exposed or were available in the source area for contribution only to the top layers of the Dunvegan Formation.

Other rock fragments: Here are included sand-size fragments of siltstone, argillite and schist. These rock fragments are present in all thin sections but were not distinguished for many fragments of intermediate composition are also present.

Some argillaceous rock fragments show silicification to varying degrees. The most characteristic types of silicification are: (a) microveins (from a few microns to 30 microns thick) of microcrystalline quartz); (b) "porphyroblastic" quartz (from about 5 microns to 30 microns in size), usually rounded but commonly with irregular arrangement. (Where the arrangement is regular, which is not infrequent, the shaly fragment looks like a cherty shale).

Fragments showing schistosity are also common. In most cases they appear to be mica-schists.

Though some of the fragments might have been derived from slightly metamorphosed sediments, most grains are representative of a sedimentary source.

Matrix

The interstitial space is occupied by clay minerals as matrix. Its percentage varies from 5 to 10.

Cement

Cement is absent from all samples except H133, 144 and 244 where it is present as a carbonate. Number 144 has about 20 per cent cement while the other two show 35 to 40 per cent.

No overgrowths on grains were observed in the sections examined.

Classification of Sandstones

A classification of sediments may be designed either to convey a clear descriptive picture of the rock in question or to bring out its genetic relations to other rocks (Rodgers, 1950). The second type of classification is based on descriptive elements of genetic value, but little agreement exists on the choice of such elements.

Klein (1963), in a review of sandstone classifications, has summarized the criteria on which different authors base their classifications:

(1) composition (denoting provenance);

(2) mineralogical maturity;

(3) textural maturity;

(4) fluidity factor (index of fluid viscosity and density measured by the per cent of clay matrix);

(5) diastrophism;

(6) primary structure.

It is obvious that a genetic classification encompassing all possible effects and their combinations must be large and complicated. Hence, the absence of any classification utilizing all of the above criteria.

Mineralogical composition of a sandstone has always been assumed to be most significant of its source, and accordingly, this has been taken as the basis of sandstone classification by many workers; for example, Krynine (1940, 1948) and Pettijohn (1943, 1949). Other criteria listed above, have been used more or less as modifiers. The general pattern followed in most classifications has been to recognize three detrital end members. However, the choice of assigning different rock constituents to these end members has not attained uniformity.

In order to plot the counts of rock-forming constituents, the writer has followed the classification scheme of Travis (1955). According to this plan, most samples are classified as "lithic sandstone" while others are "rock fragment sandstone".

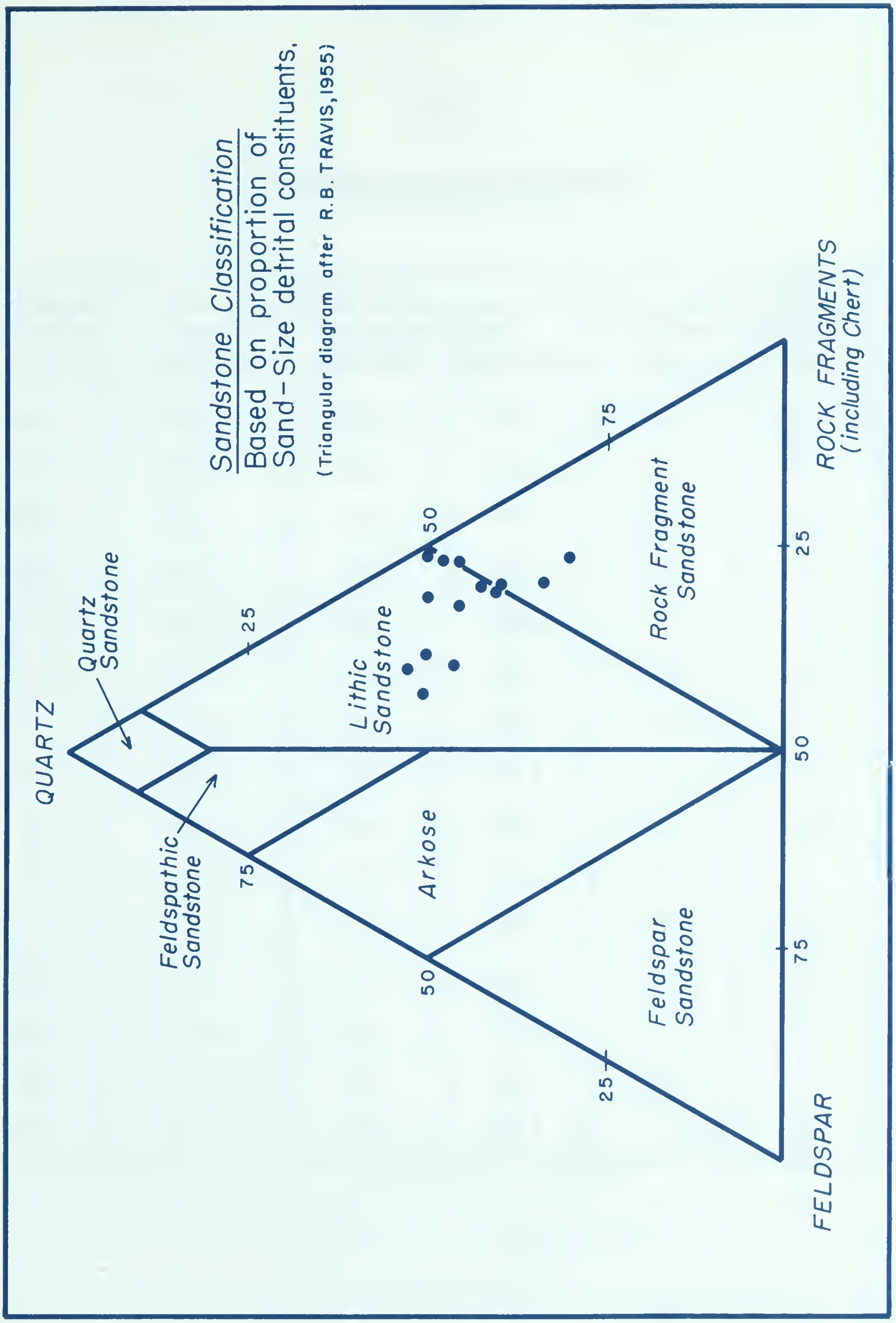

Sandstone Classification
Based on proportion of
Sand-Size detrital constituents.
(Triangular diagram after R.B. TRAVIS, 1955)
QUARTZ
FELDSPAR
ROCK FRAGMENTS
(including Chert)
Quartz Sandstone
Feldspathic Sandstone
Lithic Sandstone
Arkose
Rock Fragment Sandstone
Feldspar Sandstone
25
50
75
25
50
75
25
50
75

Figure 8.

Table 7

Percentages of Quartz and Feldspar

Sample number	QUARTZ			FELDSPAR		
	"Common" quartz (a)	"Composite" quartz (b)	Total quartz (a+b)	K-feldspar (c)	Plagioclase (d)	Total feldspar(c+d)
H6	20.0	19.6	39.6	8.5	1.5	10.0
H30	32.8	13.6	46.4	14.9	1.9	16.8
H58	46.1	3.2	49.3	12.5	1.2	13.7
H88	49.6	0.6	50.2	16.2	1.7	17.9
H133	44.2	5.2	49.4	1.3	0.4	1.7
H150	29.8	3.4	33.2	11.9	0.8	12.7
12	41.6	3.4	45.0	9.7	-	9.7
39	40.0	3.4	49.4	6.2	0.1	6.3
66	29.3	0.5	29.8	11.1	0.8	11.3
86	43.5	2.6	46.1	4.3	-	4.3
117	36.2	1.9	38.1	10.0	0.4	10.4
144	51.7	1.3	53.0	13.8	0.4	14.2
169	30.8	16.9	47.7	2.3	0.4	2.7
188	29.4	12.6	42.0	8.7	-	8.7
232	30.1	10.3	40.4	1.0	0.3	1.3

Table 8

Percentage of Rock fragments

Sample number	Chert		Volcanic fragments	Fragments of Carbonate Rock(s)	Others (i.e silt-stones, argil-lites, etc.	Total Rock Frag-ments
	Subindivi-duals equi-dimensional	Subindividuals not equi-dimensional				
H6	20.0	1.1	4.0	-	24.0	49.1
H30	12.3	0.6	-	-	23.6	36.5
H58	17.1	0.3	-	-	19.3	36.7
H88	3.3	0.5	3.2	-	25.3	32.3
H133	11.2	0.7	-	-	36.7	48.6
H150	12.2	0.6	-	-	40.9	53.7
12	7.1	0.4	-	-	37.5	45.0
39	10.1	0.4	-	-	33.6	44.1
66	7.0	0.2	-	-	50.9	58.1
86	10.8	0.2	-	-	38.5	49.5
117	10.0	0.1	0.8	-	40.2	51.1
144	11.2	0.3	0.16	-	20.9	32.5
169	8.4	0.6	2.6	-	37.7	49.3
188	11.9	1.3	-	-	35.7	48.9
232	14.9	1.5	-	10.3	31.4	47.8

CHAPTER FIVE

GEOCHRONOLOGY

Introduction

The fact that the Dunvegan sandstones are generally feldspathic and that orthoclase and sanidine together form about 10 percent of the total detrital grains, forms a basis for further examination of the source area in the light of dates yielded by these minerals. Two samples, namely, sample H6 and 188 from the lower and upper parts, respectively of the Dunvegan Formation (Figure 2) were selected for K-Ar dates.

The principle underlying the method of potassium-argon age determination is the assumption that K^{40}, in part, decays to Ar^{40} at a slow but constant rate. This argon 40, which is trapped in the crystal lattice of the minerals, is extracted and measured. The other decay product of potassium 40 is calcium 40. K^{40}-Ca^{40} decay is not used in age determination in view of the abundance of normal Ca^{40} in nature (Rankama, 1954). The other important step in age determination involves the measurement of potassium. Processes for measurements of argon and potassium have been recently described in detail by Peterman (1962) and Shafiqullah (1963). A summary of the analytical procedures and calculations followed is given below.

Potassium Determination

This was done gravimetrically by the tetraphenol boron precipitation method. The values obtained are usually given in per cent K_2O, which is converted to parts per million of K^{40} by a factor (1.0022) for the sake of subsequent calculations. Thus, per cent $K_2O \times 1.0022$ = parts per million of K^{40}.

Argon Extraction

Radiogenic argon 40 is extracted from feldspars by fusing them with a flux (NaOH) and by allowing the gas to accumulate in a closed system, as described by Goldich *et al*. (1961, p. 13-16). A known quality of Ar38 (spike) is introduced in the system to mix with the released radiogenic argon. The total argon in the system is then allowed to pass through different traps in the extraction train for the purpose of purification. Finally, only argon enters the charcoal trap where it is allowed to accumulate. The charcoal trap is then sealed off and detached from the train.

Isotopic Measurements of Argon

The argon analyses were determined using a 60° Nier-type mass spectrometer. The mass spectrometer measures the relative abundance of Ar^{40}, Ar^{38} and Ar^{36} present in the gas sample. The argon determinations were done using both the static and dynamic techniques. With the former, only a limited flow of argon is allowed at one time into the mass spectrometer through a molecular leak. In case of the dynamic technique, the flow of gas is continuous and is pumped away continually. The mass spectrometer is more sensitive under static vacuum conditions.

In general practice, in order to check on the accuracy of the mass spectrometer, the isotopic composition of a sample of air argon is determined. Any deviation from the known composition of atmospheric argon (referred to as mass discrimination) is recorded, and corrections for this are applied in the calculations.

Prior to the introduction of the gas sample in the mass spectrometer, a residual blank is determined. This is done to account for the amount of material with masses 40, 38 and 36 already present in the mass spectrometer. Corrections for these residual values are made in subsequent calculations.

Calculations

For accurate calculation of the date, it is essential that the correct ratio between Ar^{38} (from spike only) and Ar^{40} (from mineral only) be determined. Contribu-

tions of these isotopes from other sources, as outlined below, must therefore be deducted:

$$Ar^{40} \text{ radiogenic} = Ar^{40} \text{ total} - (Ar^{40} \text{ spike} + Ar^{40} \text{ air} + Ar^{40} \text{ residual})$$

$$Ar^{38} \text{ spike} = Ar^{38} \text{ total} - (Ar^{38} \text{ Air} + Ar^{38} \text{ residual})$$

$$Ar^{36} \text{ air} = Ar^{36} \text{ total} - (Ar^{36} \text{ residual} + Ar^{36} \text{ Spike})$$

The following steps are taken for the calculation of age:

(1) Total and residual values of Ar^{49}, Ar^{38}, and Ar^{36} are read from the strip chart.

(2) Ar^{38} correction from the air is ignored for it is negligible.

(3) From the known composition of spike, Ar^{36} spike and Ar^{40} spike are calculated. For the spikes used in this work,

$$\frac{Ar^{38}}{Ar36} \text{ (in spike)} = 0.00034$$

$$\frac{Ar^{38}}{Ar40} \text{ (in spike)} = 0.075$$

(4) Ar^{40} air $= Ar^{36}$ air x 288.5 (for static run)

$= Ar^{36}$ air x 302.6 (for dynamic run)

Though the known Ar^{40}/Ar^{40} value for air is 295.5, the values used above are as determined by the mass spectrometer.

(5) After applying the above corrections, Ar^{38}/Ar^{40} ratio is obtained.

(6) The Ar^{38}/Ar^{40} ratio is then corrected for mass discrimination. In this case the mass discrimination factor used is 0.988.

(7) $$Ar^{40} \text{ cc STP/gm} = \frac{\text{cc STP } Ar^{38}}{\text{gms sample x corrected } Ar^{38}/Ar^{40}}$$

(8) The volume of Ar^{40} is converted to parts per million by a factor, namely 1.7846×10^{3}.

(9) The ratio of Ar^{40} to K^{40} is then calculated and substituted in the following equation:

$$t = 4.308 \times 10^{9} \log [\ 1 + Ar^{40}/K^{40}(9.08)\ ] \text{ m.y.}$$

Results and their Interpretations

Dates obtained from the two samples are tabulated on page 58. The feldspars in the lower sample (H6) give a date of 147 m.y., and those in the upper sample (188) 155 m.y. (Table 9). To check the results of H6, the feldspars were analyzed again. The K_2O content and the date of the feldspars in this second concentrate were lower than in the first. It was also observed that the sanidine in the first concentrate formed about two-thirds of the K-feldspars, whereas in the second concentrate sanidine formed about 60 per cent and orthoclase 40 per cent. The lower value returned by the second concentrate is also partly due to the higher amount of impurities (mainly volcanic fragments) present. In case of sample 188 (from upper part of the formation), sanidine forms two thirds of the K-feldspars.

It must be recognized that the dates obtained are from detrital feldspars that were probably derived from more than one source. Nevertheless, the dates contribute some information on the source of the sediments. The ages obtained coincide with Late Jurassic orogenies in the Cordillera. Dates in this range have been reported by Baadsgaard et al (1961) from the Topley (163 m.y.) pluton, and by the Geological Survey of Canada (Lowdon, 1960) from the Yukon complex (140 and 176 m.y.).

It is significant to note that the upper part of the formation has yielded an older date (155 m.y.) and the lower part a younger one (147 m.y.). This inversion of dates in the detrital feldspars of the Dunvegan Formation supports the idea that the detritus was contributed by continuous unroofing of slowly rising Cordilleran batholiths to the west.

Table 9

K-Ar Dates from Dunvegan Formation, Type Area

Field Sample No.	Geology Dept. No.	Stratigraphical Position in the Fm.	Radiogenic Argon in %		K_2O%	Dates in million years		
			Static	Dynamic		Static Run	Dynamic Run	Average
H6	AK 507A	6 feet from 'base' of Fm.	94.0	94.0	7.580	146.0	148.0	147.0
-do-	AK 509	-do-	89.0	89.0	6.230	132.0	130.0	131.0
188	Ak 510	338 ft. from 'base' of Fm.	96.0	95.0	8.510	157.0	153.0	155.0

N.B. 1) K_2O determinations by Mr A. Stelmach, Geochemist, Dept. of Geology, University of Alberta

2) Argon analysis on a 60° Nier-type mass spectrometer by Dr. G.L. Cumming, Dept. of Physics, University of Alberta.

CHAPTER SIX

Summary and Conclusions

The Dunvegan sandstones of the type section at Dunvegan, Alberta, were examined with respect to their texture, composition, and the ages of the potash feldspars.

Textural observations were made by studying grain size distributions of 24 samples obtained from sieving and pipette analyses. The sandstones are generally fine-grained, and are poorly sorted. They contain an excess of fine material which is relatively poorly sorted compared with the coarse material of the same sample. The textural maturity of the sandstones indicates poor stability of the depositional site and/or a low energy environment. On the basis of ratios of sand, silt and clay, most sandstones are classed as 'silty sandstones'.

The sandstones contain only a few varieties of accessory 'heavy' minerals in abundance. However, these constituents give a distinctive indication of the provenance. Such mineral as apatite, euhedral zircon, sphene and pink tourmaline are generally suggestive of an igneous source. Rounded grains of tourmaline, hyacinth zircon and rutile are indicative of a sedimentary source. Garnet, chloritoid, staurolite, kyanite, glaucophane, and epidote indicate a metamorphic source. The overwhelming dominance of chloritoid in the upper layers of the formation is very conspicuous, and suggests that the low to medium rank metamorphic rocks probably supplied much of the detritus during this phase of sedimentation.

Petrographically, the rock-forming constituents are grouped under three main categories: quartz, feldspar and rock fragment. Taking these three as end members, the sandstones are classed, in general, as 'lithic sandstones' on a triangular diagram. Detrital carbonate rock fragments are absent from all samples except the two samples, representing top layers of the formation.

Cement is generally absent. No overgrowth of grains is noted. Porosity as well as matrix, for most samples, is around 5 to 10 per cent.

Chert, argillaceous and siliceous fragments, and some of the quartz are probably from a pre-existing sedimentary source. Sanidine, at least some of the orthoclase and plagioclase, and volcanic fragments indicate an igneous source. Fragmental grains of schist and some of the 'composite' quartz grains are indicative of an original metamorphic source.

K-Ar dates from feldspar concentrates of two samples coincide with the Upper Jurassic orogenies in the Cordillera. These two samples represent 'lower' and 'upper' part of the formation with a vertical difference of 332 feet. The sandstone from the 'lower' part has yielded a younger date (147 m.y.) compared to the one from upper part (155 m.y.). This inversion of dates suggests that the Dunvegan sediments were derived by unroofing of Cordilleran batholiths to the west.

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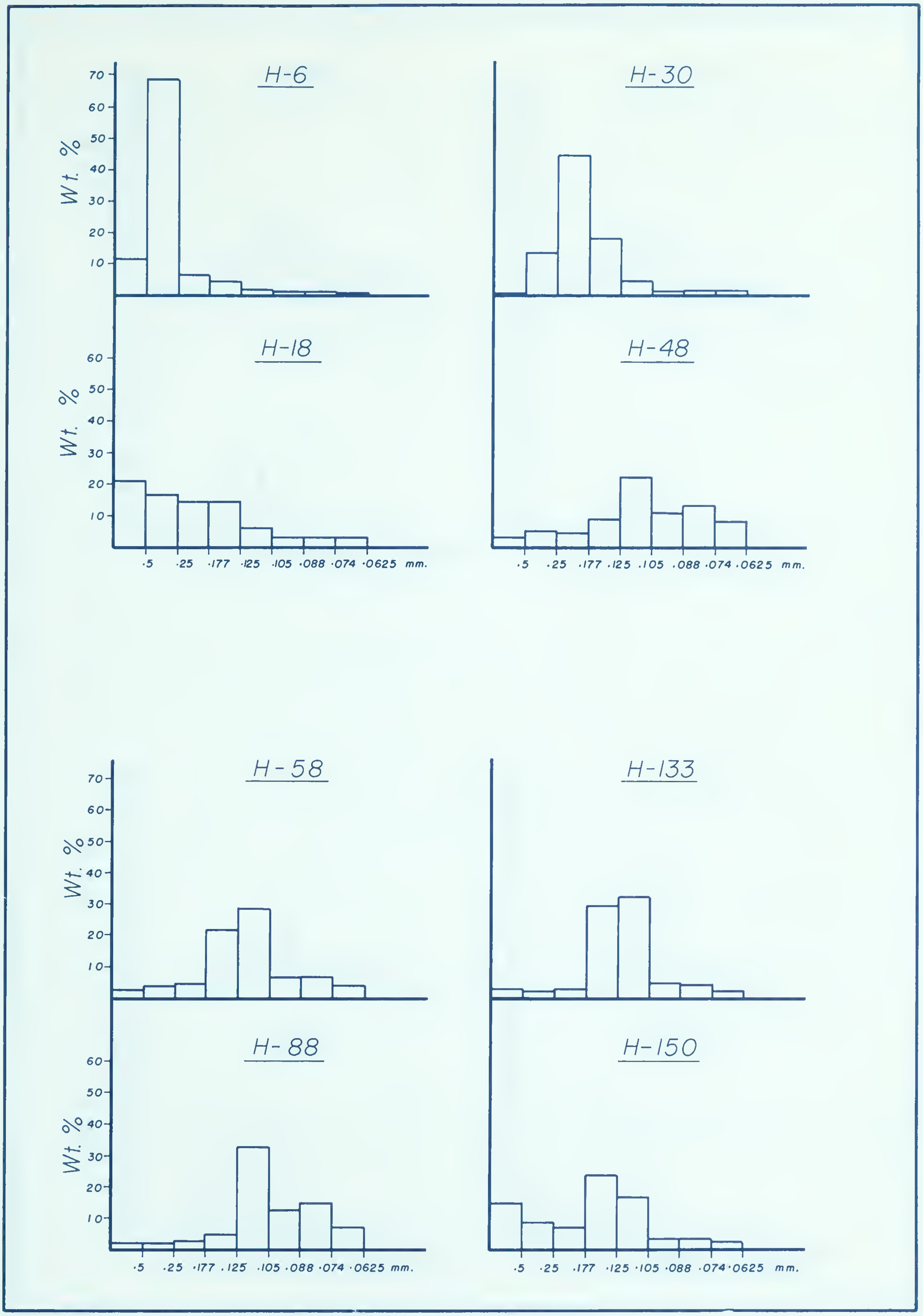
APPENDIX

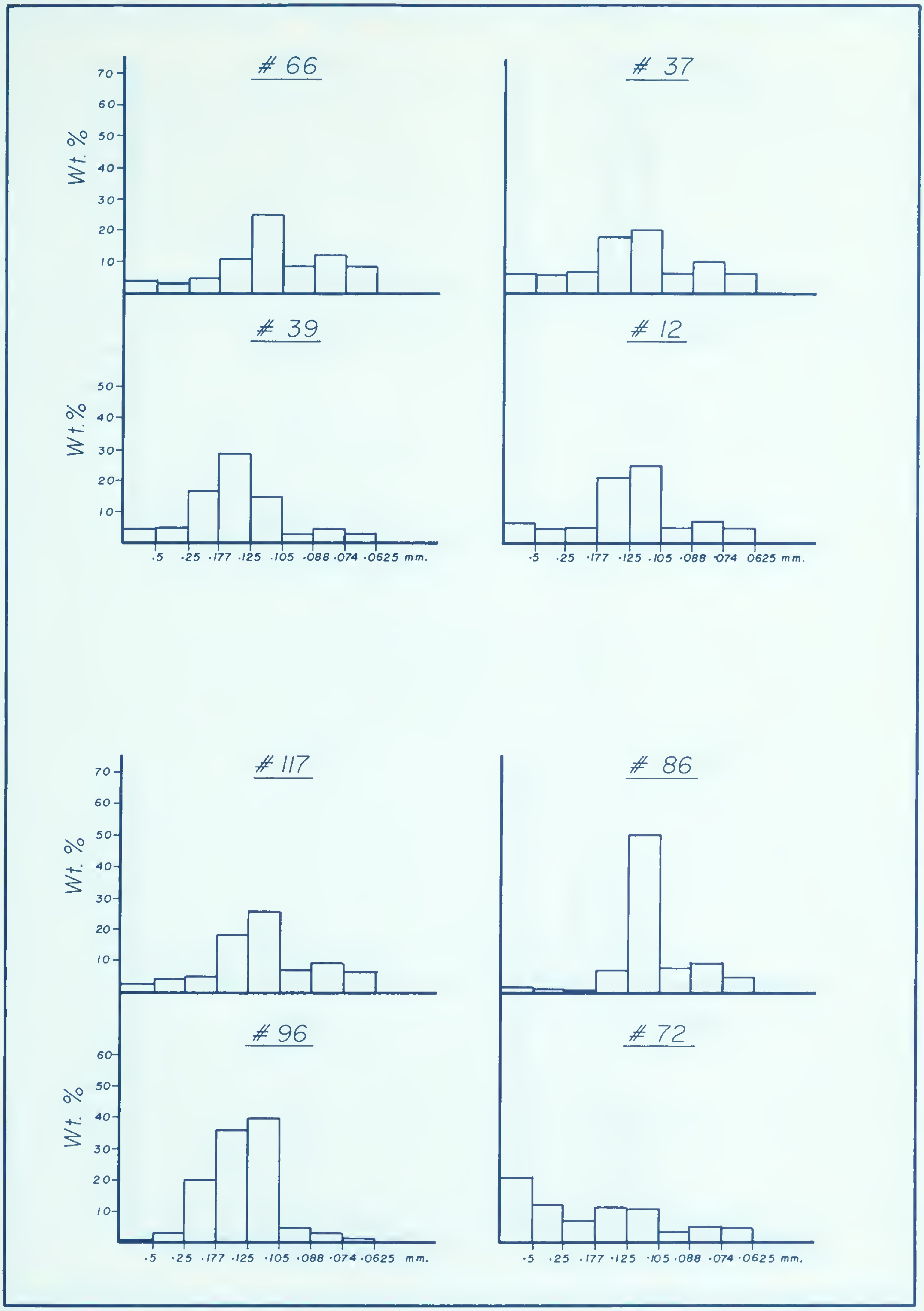
Histograms of 24 samples

Cumulative curves of 24 samples

Photographic plates

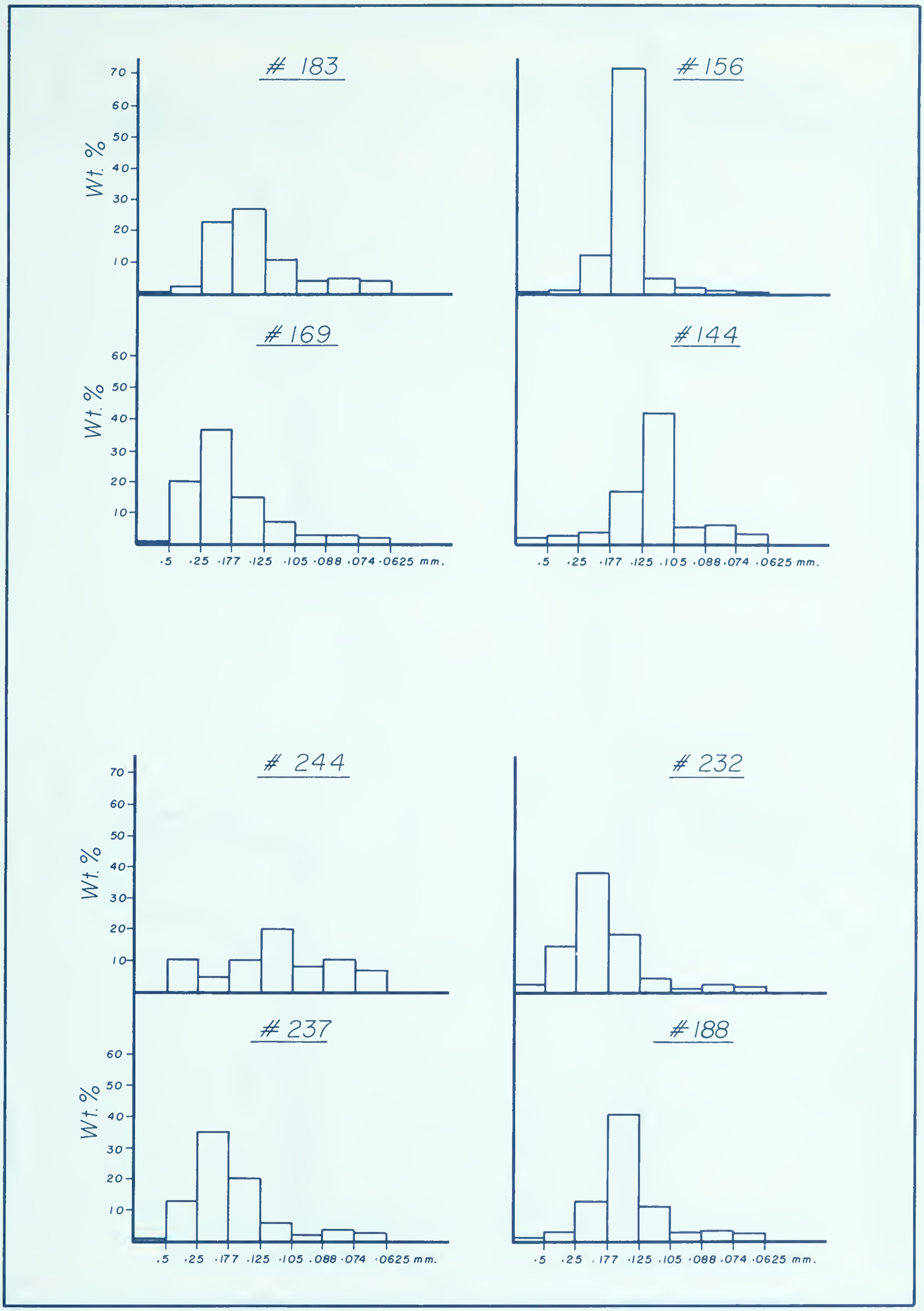


Histograms
% Weight vs. screen size.

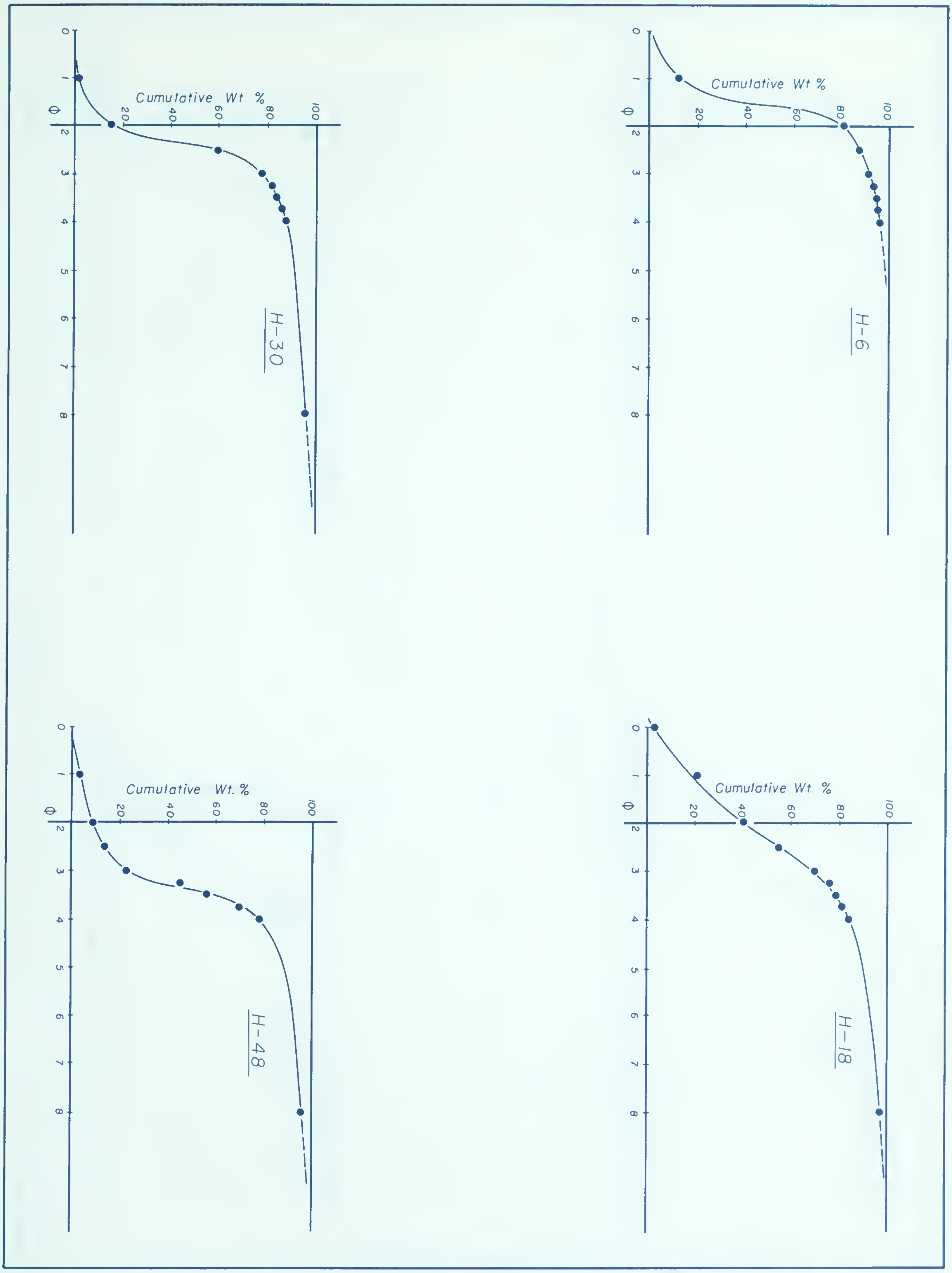


Histograms

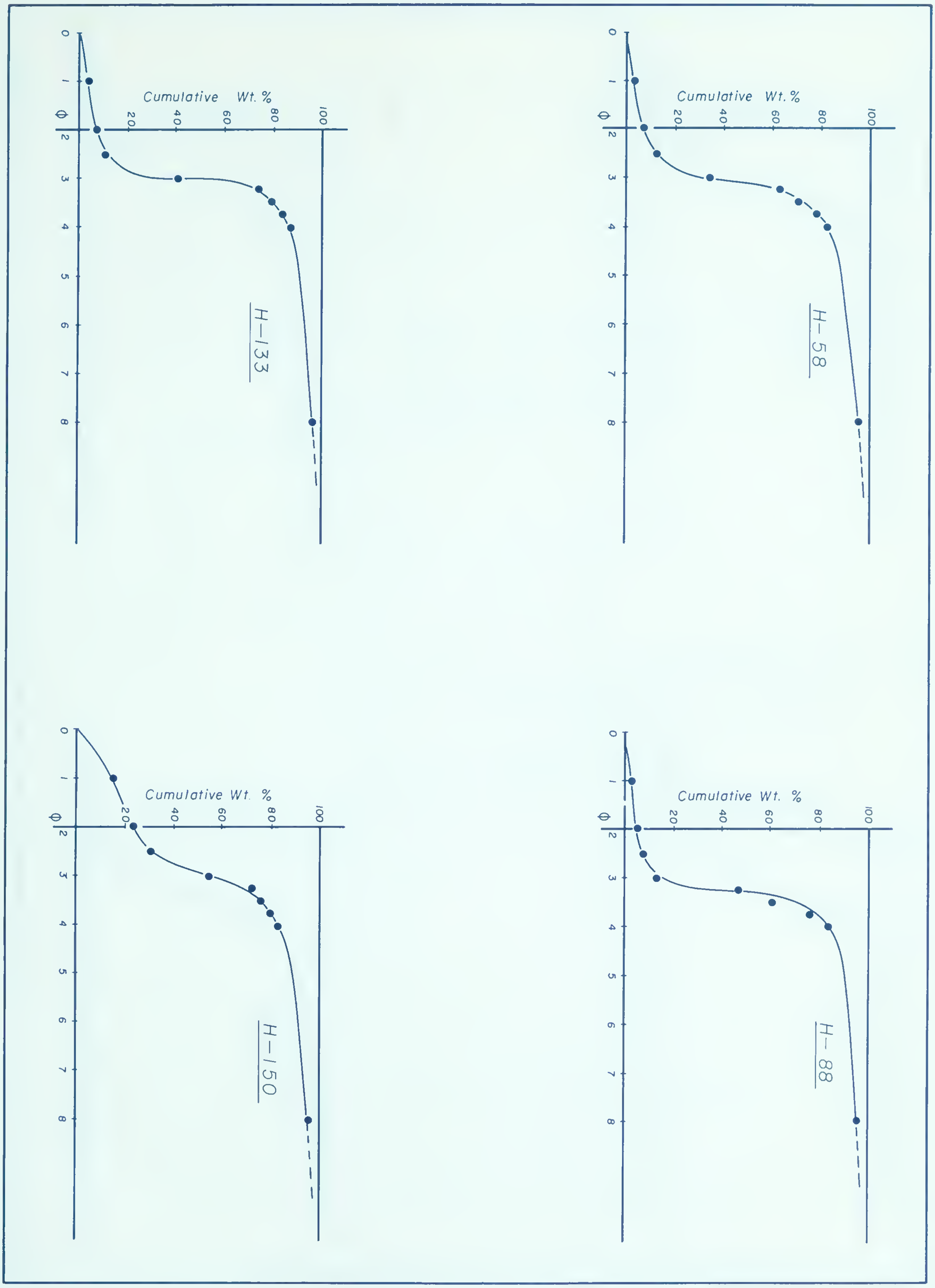
% Weight vs. screen size.



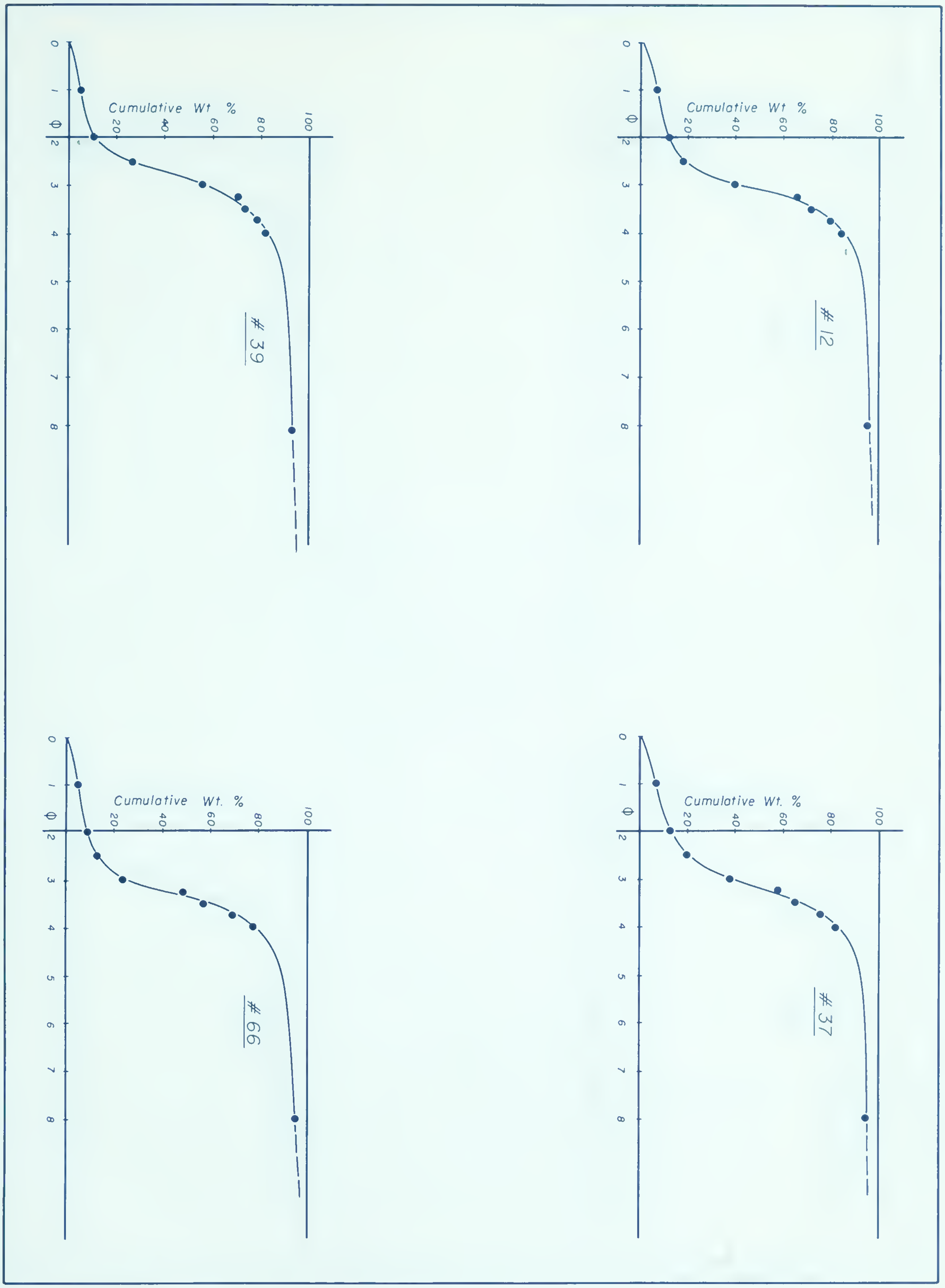
Histograms
% Weight vs. screen size.



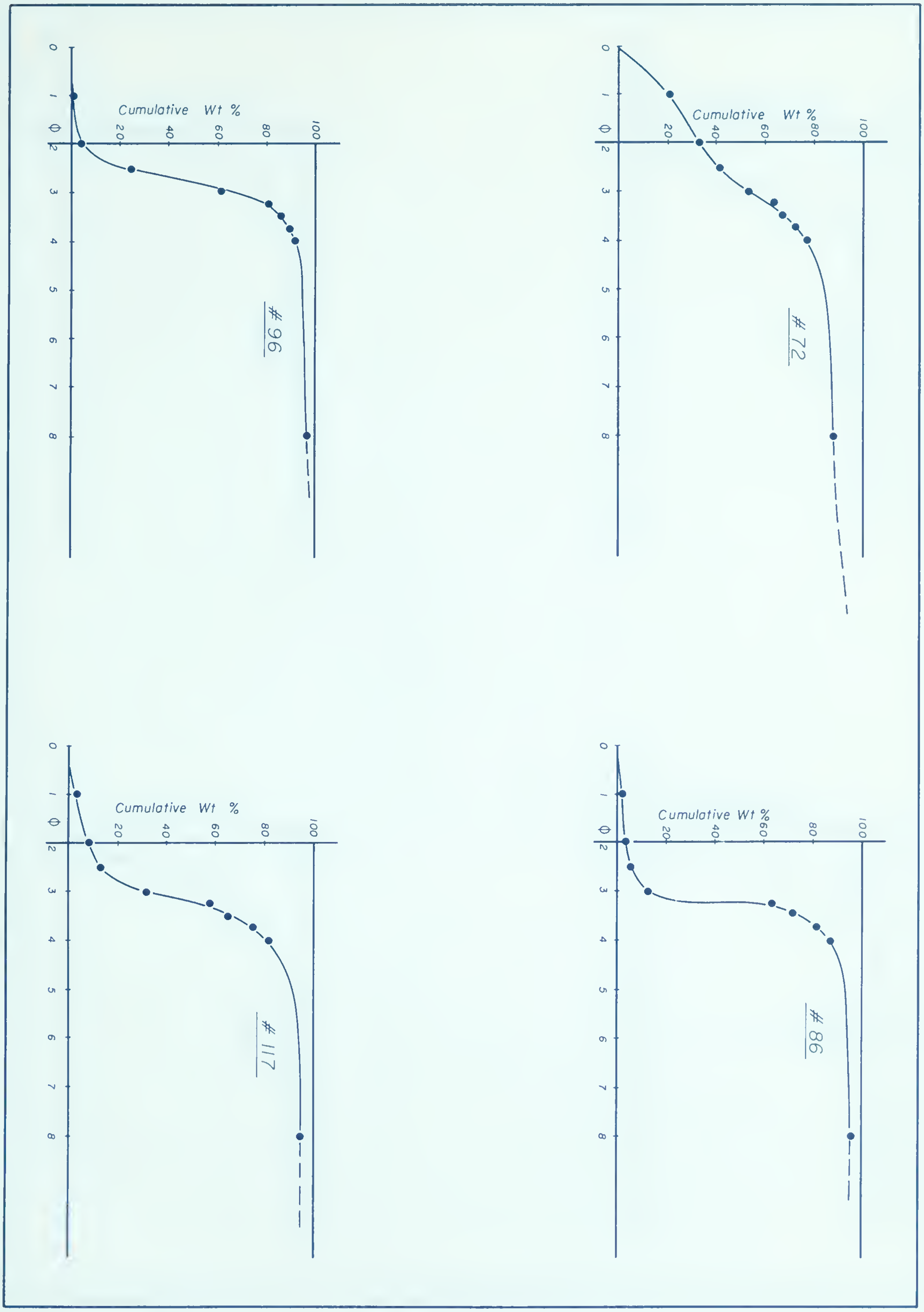
Cumulative Curves
% Weight vs. grain size.



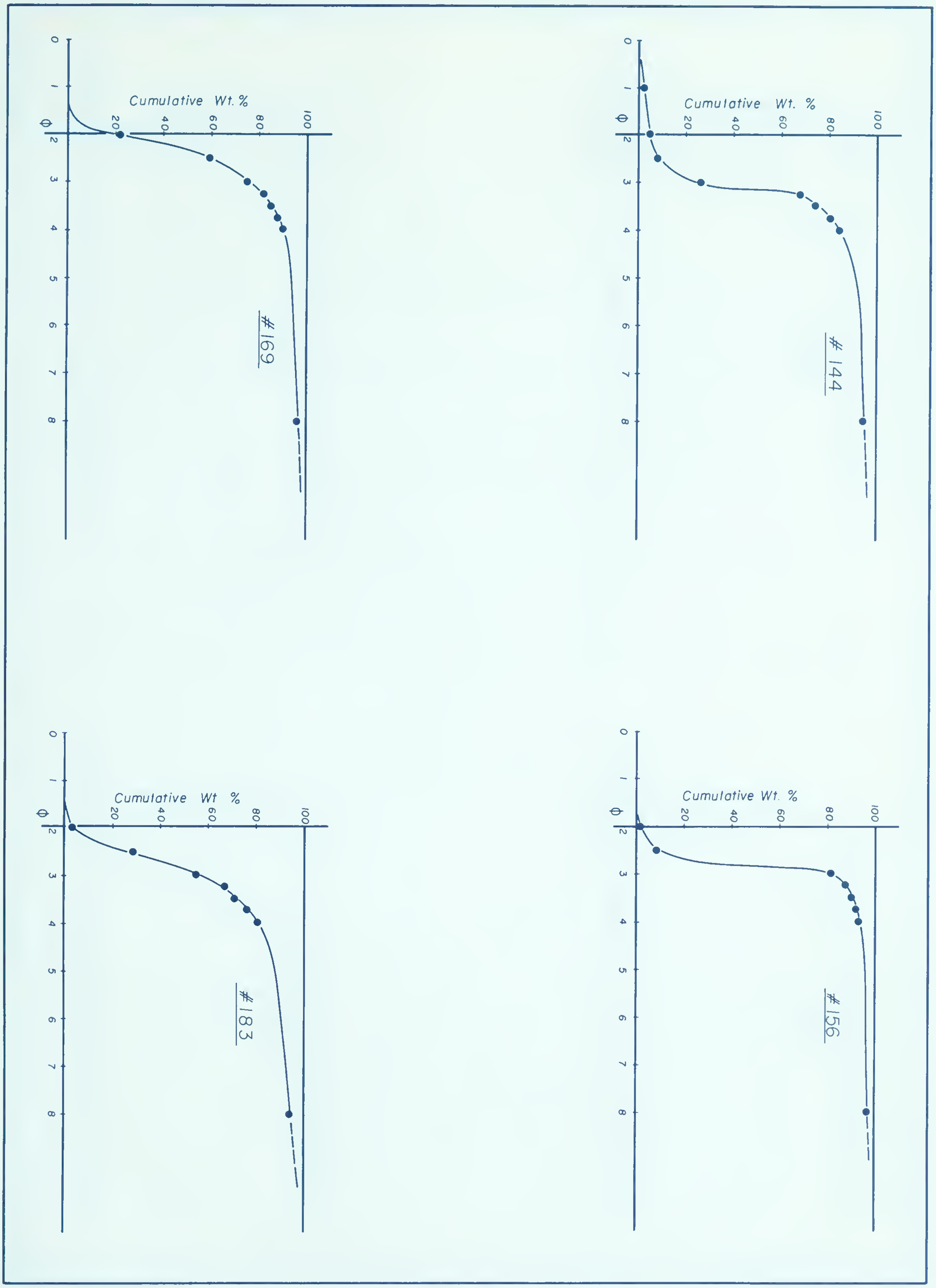
Cumulative Curves
% Weight vs. grain size.



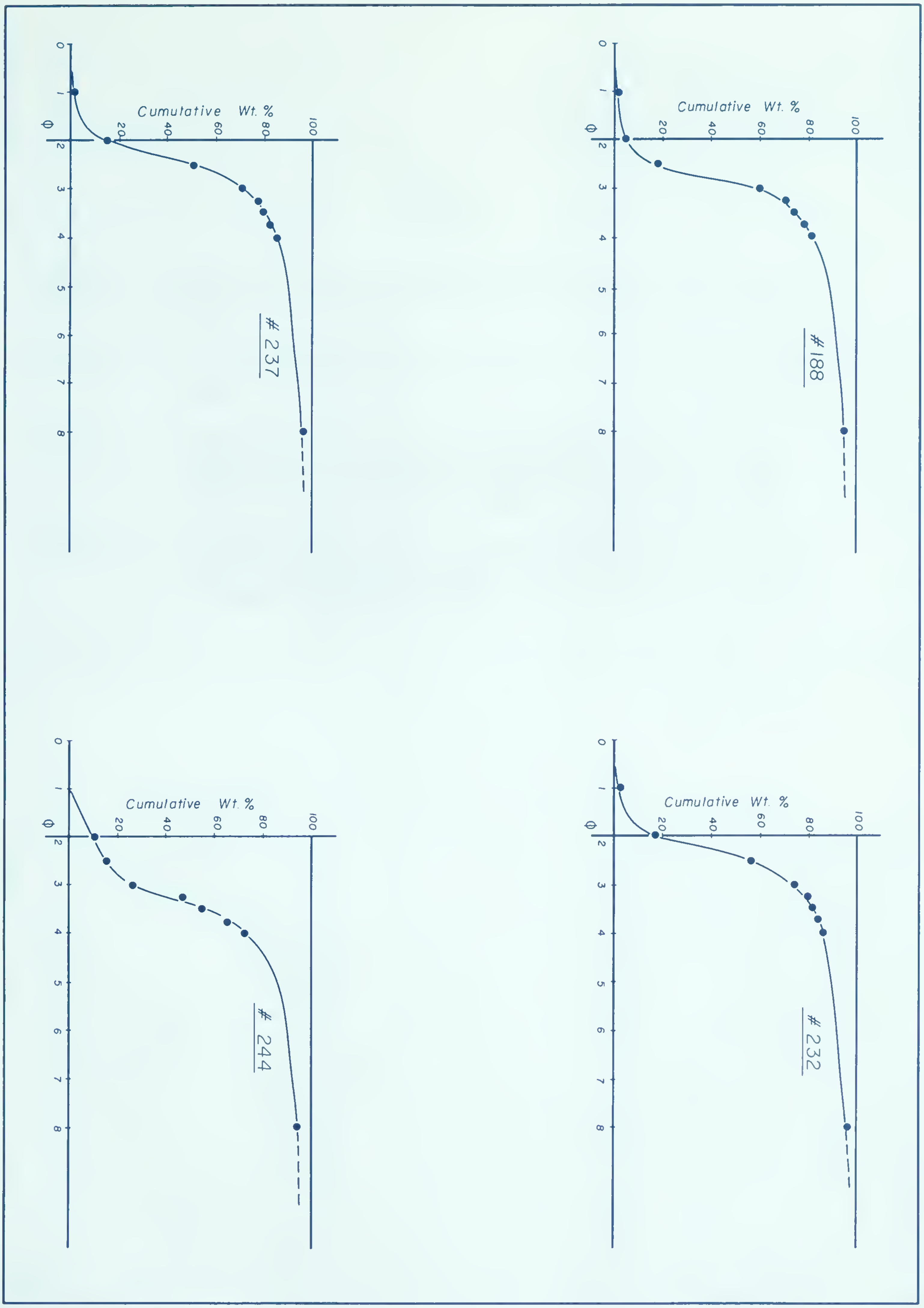
Cumulative Curves
% Weight vs. grain size.



Cumulative Curves
% Weight vs. grain size.



Cumulative Curves
% Weight vs. grain size.



Cumulative Curves

% Weight vs. grain size.

Plate - 1

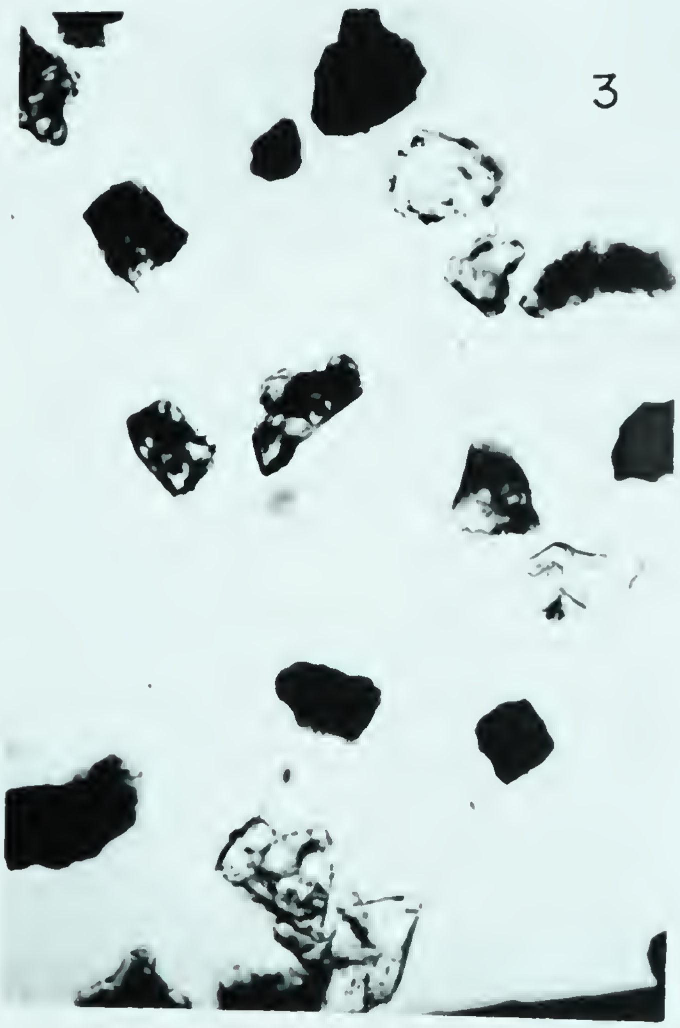
Figure 1. - Outcrop of Dunvegan Formation (upper part) at the type area.

Figure 2. - Outcrop of Dunvegan Formation (lower part) at the type area.

Figure 3. - Feldspar concentrate from sample 188. Sanidine grains almost clear, orthoclase grains cloudy. Volcanic fragments and chert grains are opaque. Magnification 48X.

Figure 4. - Sandstone (sample H30) showing grains of quartz and chert. A grain of plagioclase can be seen at the centre. Nicols crossed. Magnification 30X.

PLATE I.



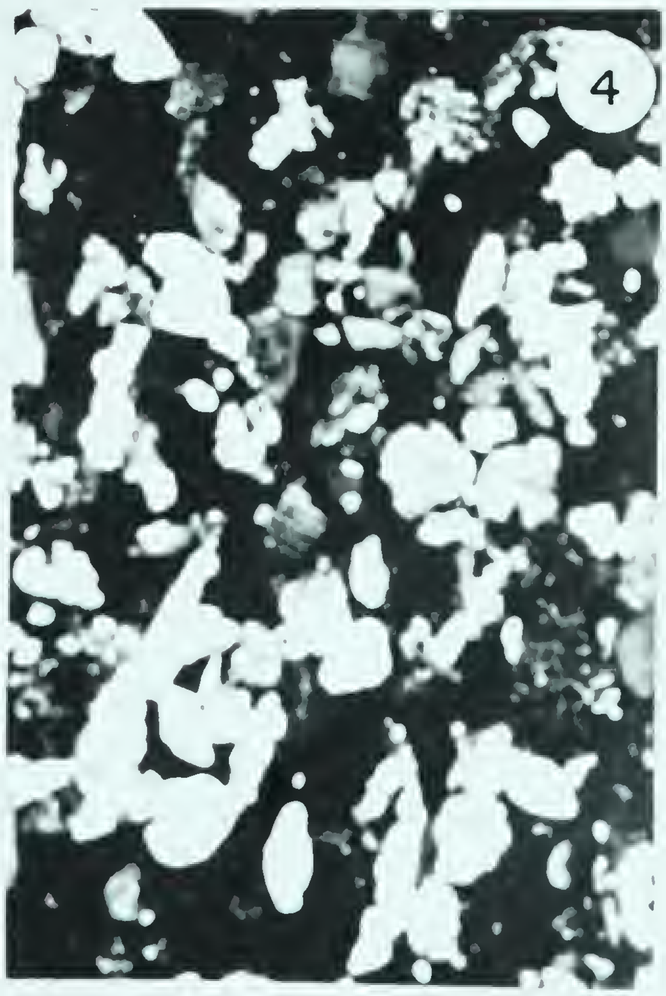


Plate - 2

Figures 1 & 2. - Slightly rounded euhedral zircon (sample H58). Note the core, overgrowth and inclusions. Magnification 480X.

Figure 3. - Euhedral zircon showing outgrowth (sample H30). Magnification 300X.

Figure 4. - Twinned zircon (sample H6). Magnification 480X.

Figure 5. - Zircon showing differences in rounding at its two ends. Also note the overgrowth. From sample 96. Magnification 250X.

Figure 6. - Rounded hyacinth (twinned ?). From sample H6. Magnification 480X.

Figure 7. - Well-rounded zircon (sample 96). Note the inclusions. Magnification 480X.

Figure 8. - Long prismatic zircon with rounded ends. Note the inclusion through out the length of the grain. From sample 96. Magnification 250X.

Figure 9. - Subrounded grain of apatite (sample H6). Magnification 300X.

Figure 10. - Staurolite with saw-tooth boundary (sample 96). Magnification 300X.

Figure 11. - Subrounded grain of apatite (sample H150). Note the arrangement of inclusions. Magnification 300X.

Figure 12. - Sphene (sample 169). Magnification 300X.

PLATE II.

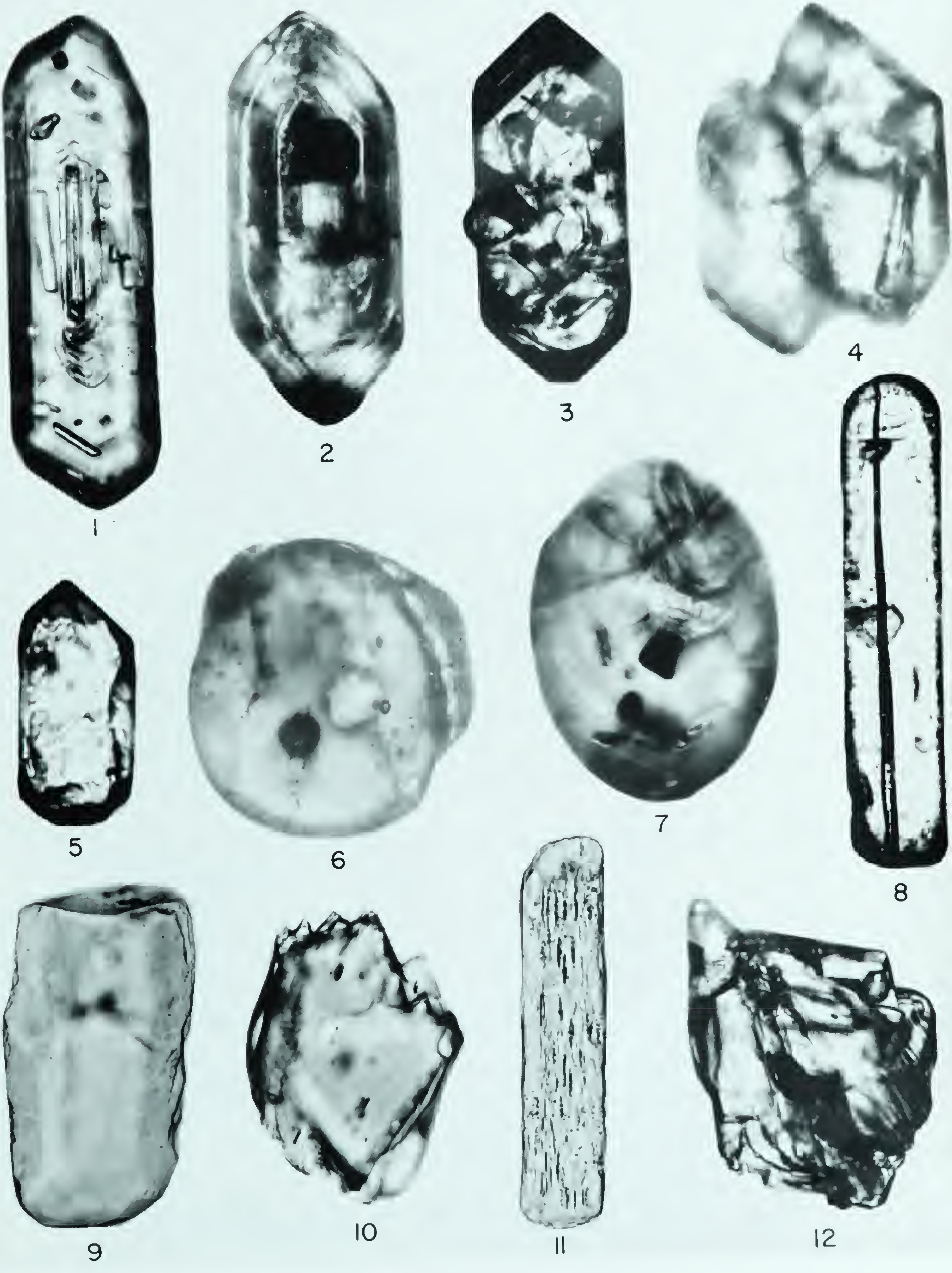


Plate - 3

Figure 1.	- Almost clear grain of sanidine (sample H6). Magnification 120X.
Figure 2.	- Subangular grain of orthoclase (sample H6). Note the arrangement of inclusions. Magnification 190X.
Figure 3.	- Rounded euhedral grain of garnet (sample 96). Note the inclusions. Magnification 300X.
Figure 4.	- Rounded euhedral rutile (sample H30). Magnification 480X.
Figure 5.	- Garnet showing conchoidal fracture (sample H150). Magnification 300X.
Figure 6.	- 'Skeleton crystal' of garnet due to solution (?). Sample H6. Magnification 300X.
Figure 7 & 8.	- Garnet grains showing corrosion due to solution effect (?). From sample 96. Magnification 190X.
Figure 9.	- Subangular grain of tourmaline with abundant inclusions (sample 144). Magnification 600X.
Figure 10.	- Garnet grain showing corrosion at its borders (sample 96). Magnification 190X.
Figure 11.	- Euhedral grain of tourmaline (sample 37). Note the inclusions. Magnification 750X.
Figure 12.	- Grain of chloritoid (sample 244). Note inclusions. Magnification 300X.

PLATE III.

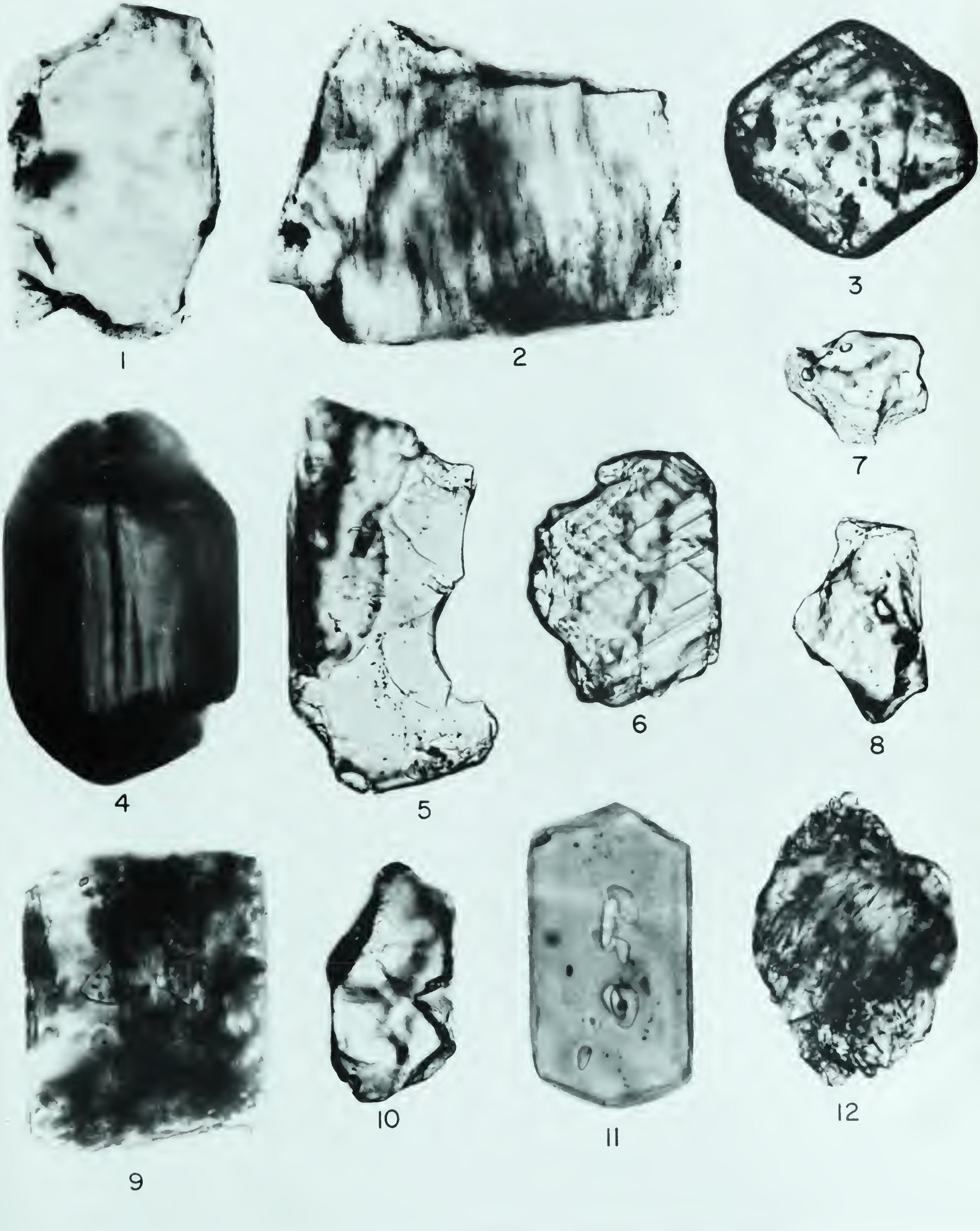


Plate - 4

Figure 1. - Sandstone (sample H6) showing grains of chert, quartz (clear ones) and feldspar (less clear than quartz). Note the rounding of feldspar (near the top of the microphoto). Nicols crossed. Magnification 30X.

Figure 2. - Sandstone (sample 169) showing quartz and chert grains with matrix. Nicols crossed. Magnification 30X.

Figure 3. - Grains with cloudy appearance are carbonate. Two such grains can be seen at the top. Sample 232. Nicols not crossed. Magnification 30X.

Figure 4. - Sandstone showing carbonate cement (sample 144). Nicols crossed. Magnification 75X.

PLATE IV.